And Now on to Higher Gains: Physics Platforms and Minimum Requirements for Inertial Fusion Energy

IFE Strategic Planning Workshop Kickoff

November 16, 2021

L. John Perkins, Design Physics Division LLNL

With thanks to: *K. Anderson, T. Collins, P. Patel, S.Slutz, A. Schmitt, T. Ma, G. Logan, M. Campbell, R. Betti, M. Murakami, A. Schmitt, S. Obenschain, B. Van Wonterghem*

Lawrence Livermore National Laboratory

LLNL-PRES-828699

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

NNSA National Nuclear Security Administration

Why high(er) gains/yields on the National Ignition Facility?

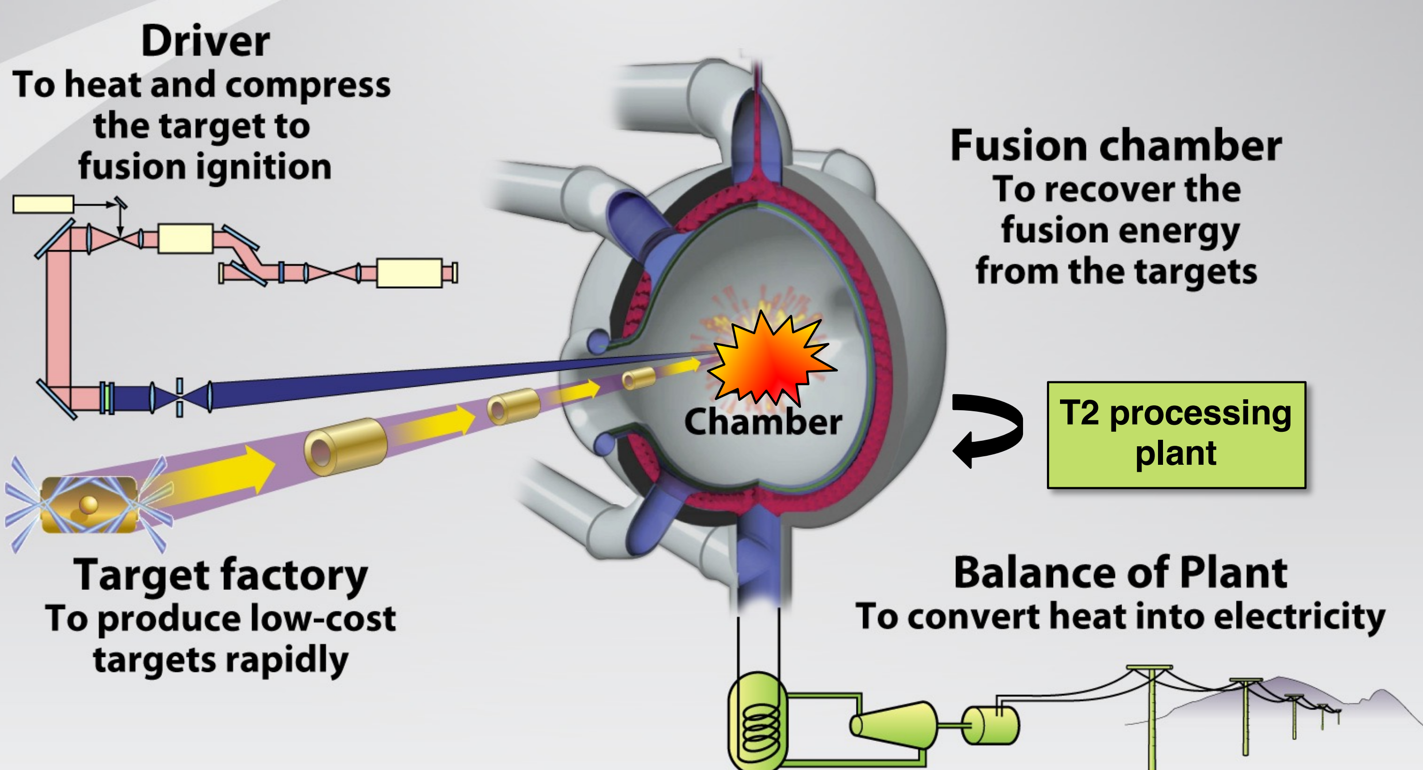
- **To establish and confirm the scaling of ignition and burn physics for the present baseline class of cryo-DT targets in indirect drive.** (Low adiabat versions of this class have typical maximum "inertial confinement" yields of $\sim\rho R/(\rho R+7)$ ~20 MJ)
- **For uses of ignition and nuclear yield for stockpile stewardship applications** (Outside of a nuclear test, only NIF can attain the conditions in the core of a nuclear device during the nuclear phase of operation).
- **For exploring the rich science of the high-energy-density-physics of thermonuclear burn** (Applications to discovery science avenues….stellar atmospheres, magnetized burn, …)
- **For Inertial Fusion Energy, ……..**

That old adage: What's the difference between ICF and IFE?

- In *Inertial Confinement Fusion (ICF)*, you have to show you can do it once
- In *Inertial Fusion Energy (IFE)*, you have to show you can do it 10-times a second for 30-years at 95% availability, 10-cents a target and a COE of 5 ¢/kWh !

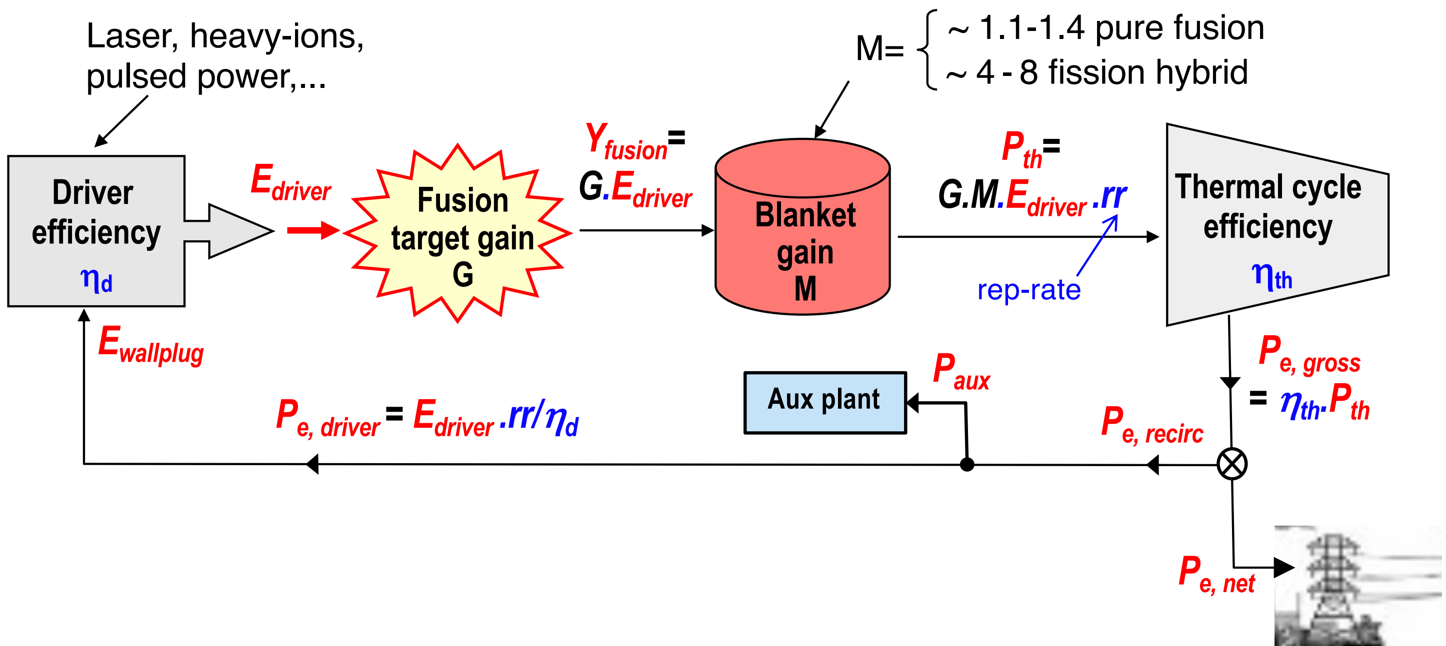
  ⇒ One essential step:- High gain targets (Strive for gains ≳100 at 1MJ)

A generic inertial fusion power plant – the components are highly separable



https://life.llnl.gov/index.php

The required fusion gains for advanced targets are determined by power plant energy-balance (and economics) – Part 1

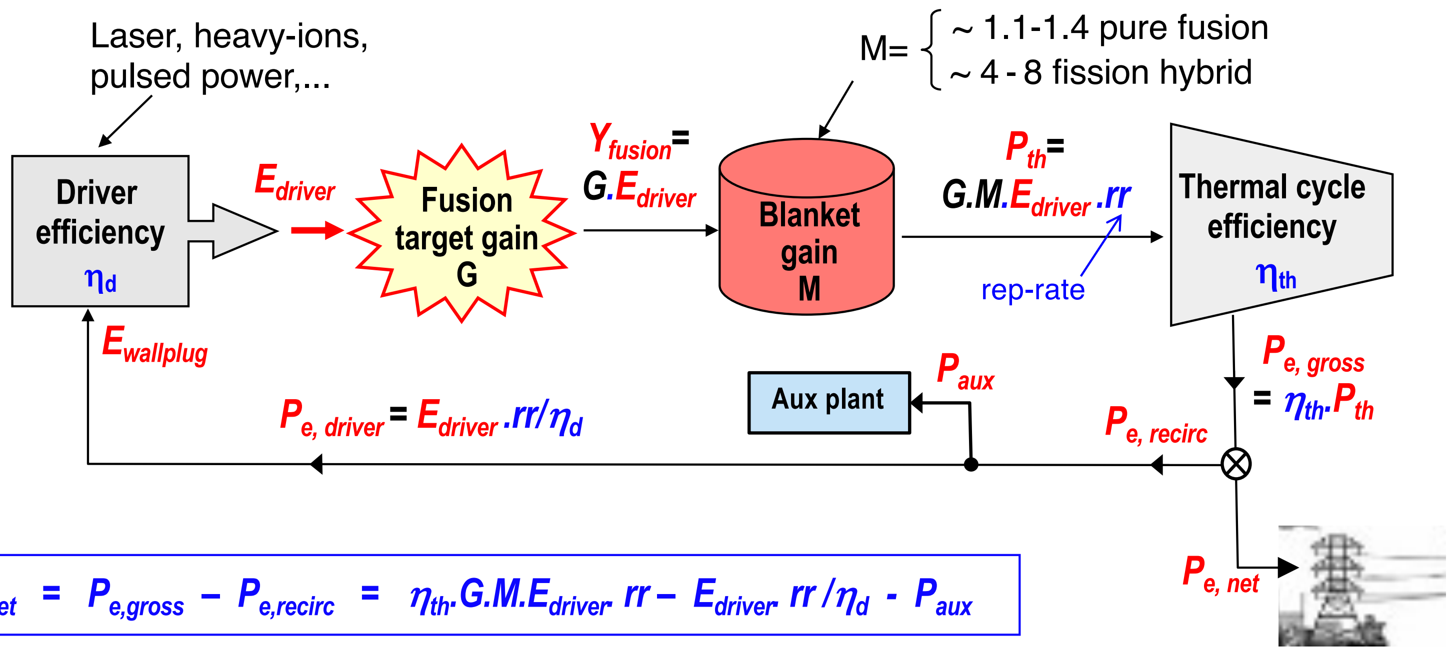


IFE economics suggest that the following are desirable:

Engineering gain: $G_{eng} = Y_{fusion} / E_{wallplug} = \eta_d G > 10$

Target gain: $G = Y_{fusion} / E_{driver} \gtrsim 100$ **@ ~1MJ (for** $\eta_d \gtrsim 0.1$**)**

The required fusion gains for advanced targets are determined by power plant energy-balance (and economics) – Part 2



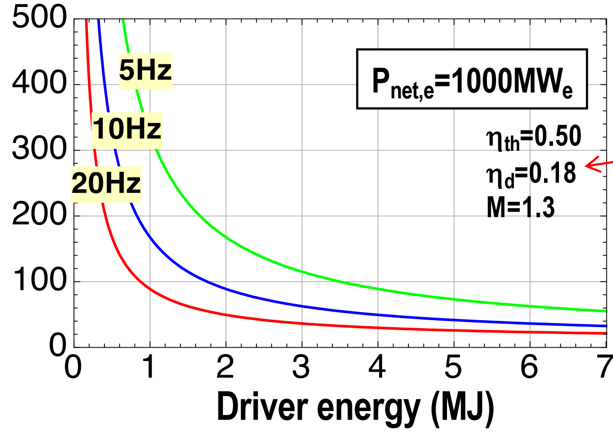
$$P_{e,net} = P_{e,gross} - P_{e,recirc} = \eta_{th}.G.M.E_{driver}.rr - E_{driver}.rr/\eta_d - P_{aux}$$

To elucidate the power dynamics and economic implications of this equation:

- **Select req'd net electric output, $P_{e,net}$**
- **Specify driver efficiency η_d + thermal cycle efficiency η_{th} + blanket gain M**
- **$\Rightarrow$ Determine <u>*required*</u> target gain G for a given driver energy E_{driver} and rep-rate rr**

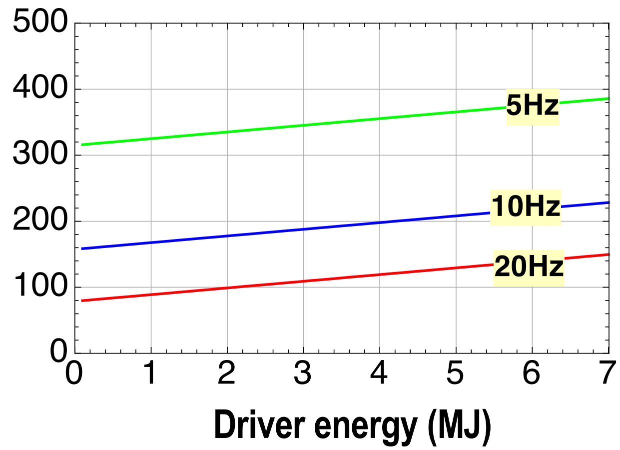
Any driver IFE: Here are the *required* target gains and corresponding yields for a $1000MW_e$ pure fusion power plant

Target gain required



Given these input assumption

Yield (MJ)

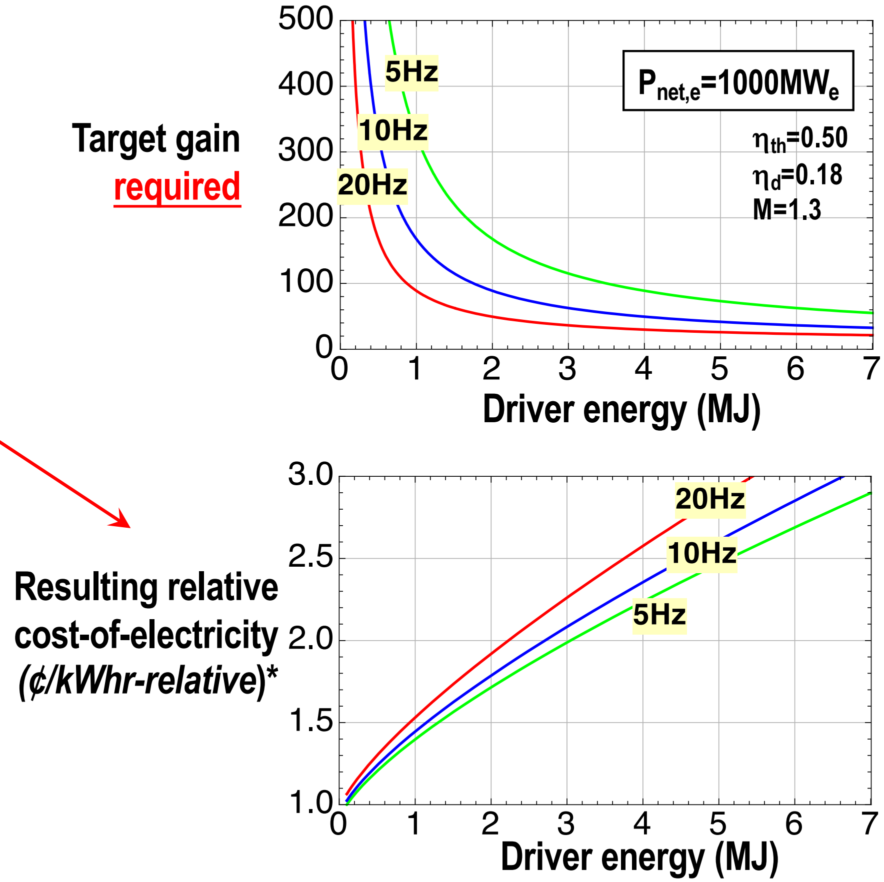


Laser IFE: Here are the economic consequences

Results of applying an economic systems model* for the whole power plant with 3ω DPSSLs as the driver, where:

COE = f ($\$_{driver}$, $\$_{chamber}$, $\$_{nucl\text{-}steam\text{-}supply}$, $\$_{BOP}$, $\$_{bldgs}$, $\$op_{targets}$, $\$op_{fuel}$, plant-life, fixed-charged-rate, capacity-factor, ….etc)

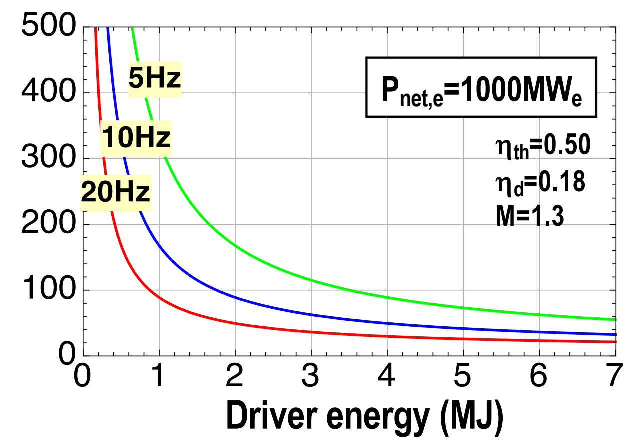
<u>But</u> will have physics and technology constraints that prevent you from operating in certain regions of this design/cost space – *<u>in particular the target gain curve</u>*



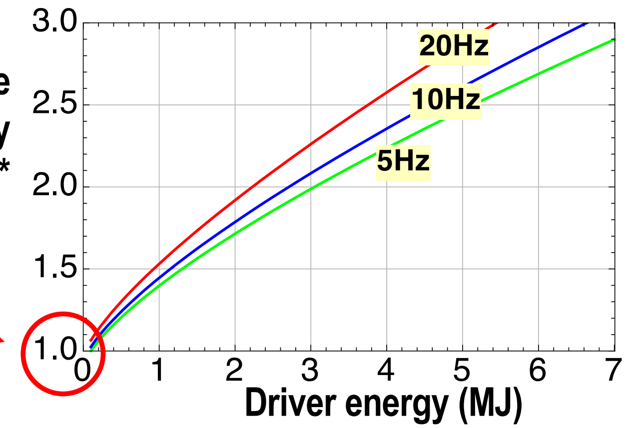
* Economic model derived from formalisms due to Logan (*Fusion Tech.*1995) ,Moir (*Fusion Tech.* 1995, *Proc ICENES-9* 1998), Yu, Meier ((*Fusion Tech.* 2003)

Laser IFE: What do these relative costs mean?

Target gain
required



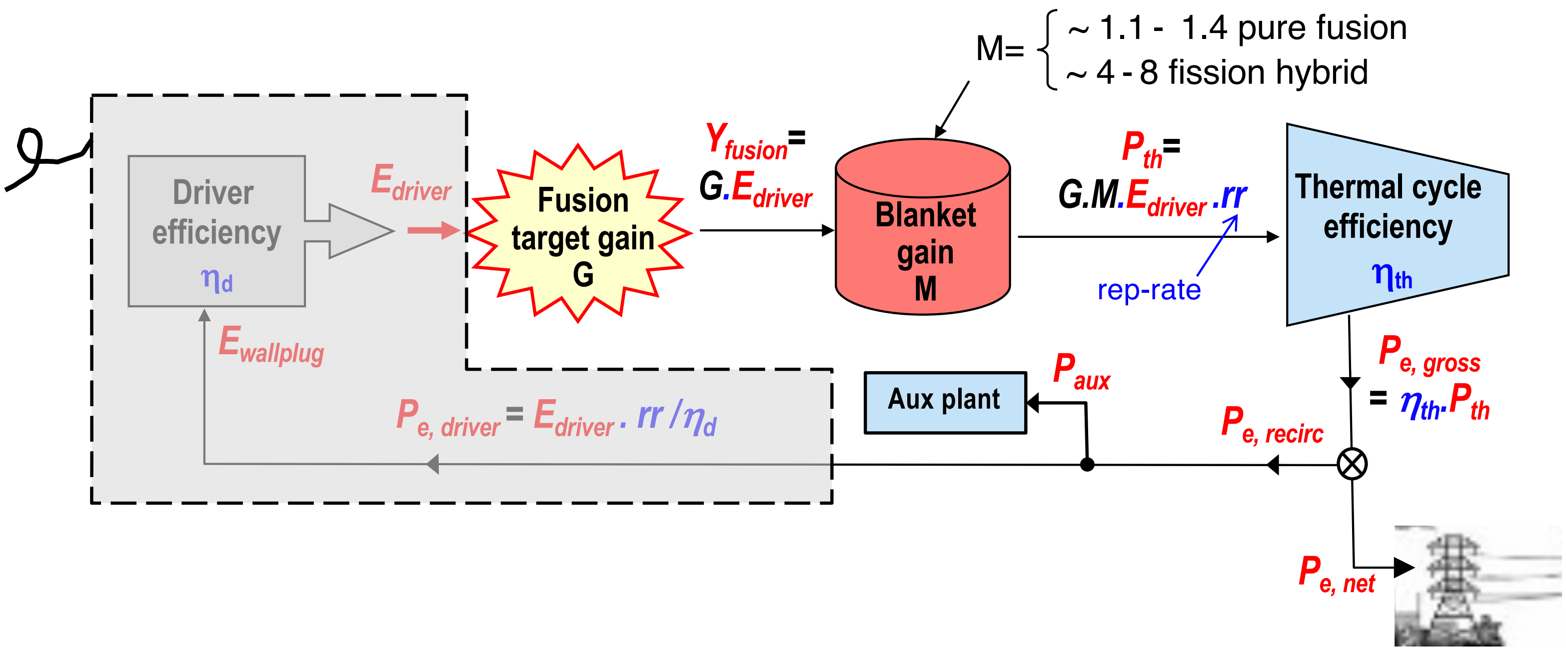
Resulting relative
cost-of-electricity
*(¢/kWhr-relative)**



Relative-COE =1 is an IFE power plant with zero driver energy and infinite target gain. What's left is the target chamber, nuclear island and balance-of-plant (~ a fission reactor to 0^{th}-order!)

* Economic model derived from formalisms due to Logan (*Fusion Tech.*1995) ,Moir (*Fusion Tech.* 1995, *Proc ICENES-9* 1998), Yu, Meier ((*Fusion Tech.* 2003)

The “zeroth-order fission reactor”

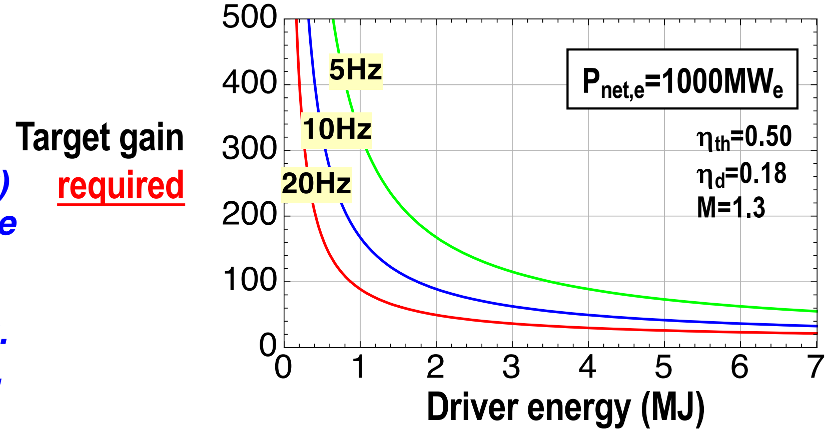


$$P_{e,net} = P_{e,gross} - P_{e,recirc} = \eta_{th} . G.M.E_{driver} . rr - E_{driver} . rr / \eta_d - P_{aux}$$

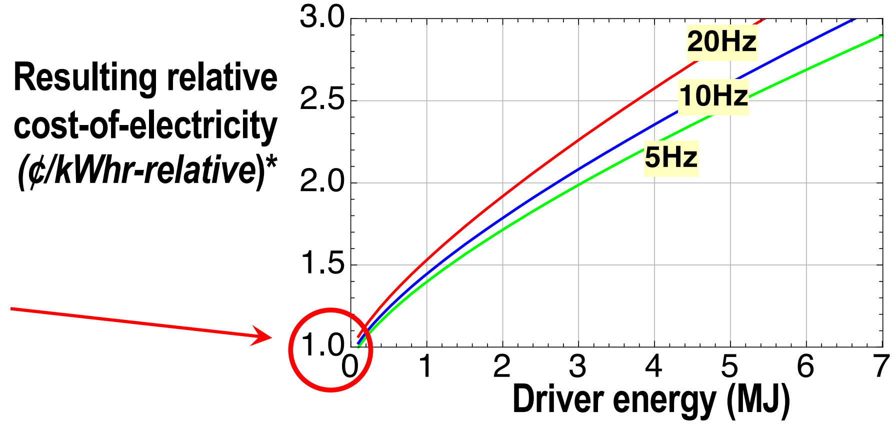
Laser IFE: Don't forget the important external advantages of fusion!

***But** doesn't imply that the IFE nuclear island (incl driver) must reduce to the size/complexity of a fission core to be competitive (likely a physics impossibility).*

Fusion has crucial external advantages over fission, e.g. safety + environment, waste disposal, non-proliferation, fuel cycle…etc, that can redress the balance

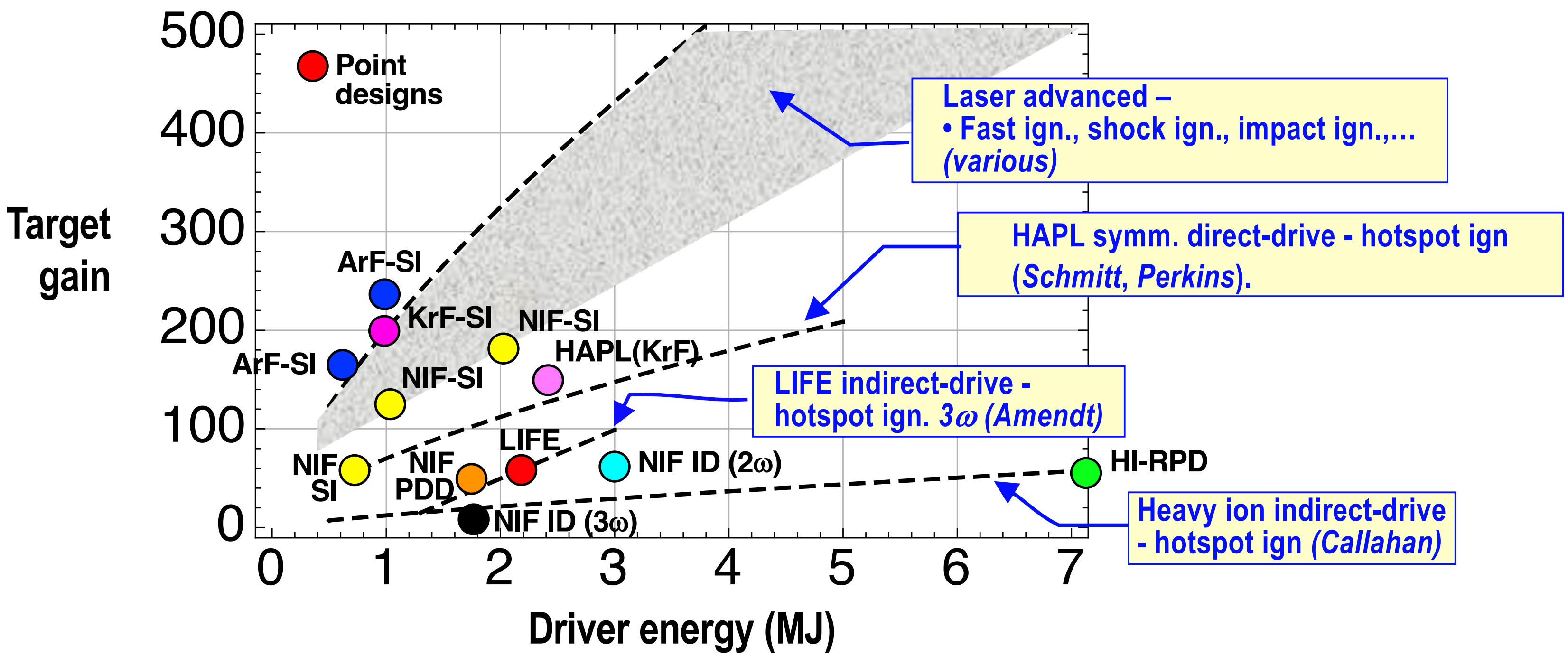


Relative-COE =1 is an IFE power plant with zero driver energy and infinite target gain. What's left is the target chamber, nuclear island and balance-of-plant (~ a fission reactor to 0th-order!)



* Economic model derived from formalisms due to Logan (*Fusion Tech.*1995) ,Moir (*Fusion Tech.* 1995, *Proc ICENES-9* 1998), Yu, Meier ((*Fusion Tech.* 2003)

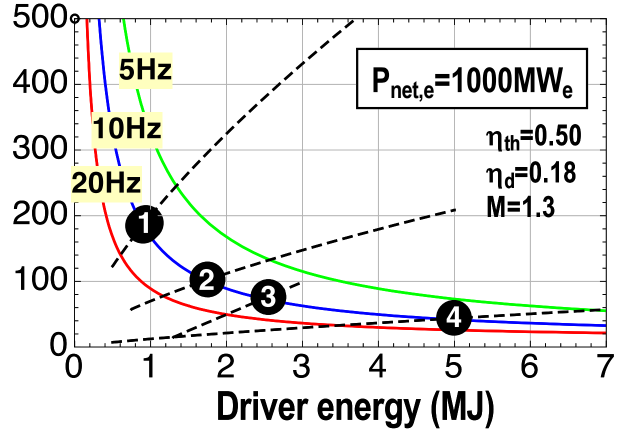
But what target gains might we achieve? Projected gain curves...



(See later in presentation for details of these gain curves)

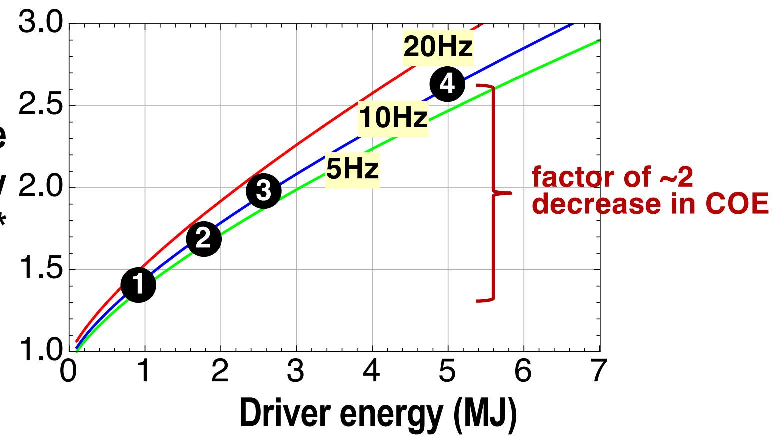
Laser IFE: Now overlay what we might achieve over what we need....

Target gain required



x = operating points for specific target gain curves at 10Hz rep-rate

Resulting relative cost-of-electricity *(¢/kWhr-relative)**



* Economic model from scalings due to Logan (*Fusion Tech.*1995) ,Moir (*Fusion Tech.* 1995, *Proc ICENES-9* 1998), Yu, Meier ((*Fusion Tech.* 2003)

Some take aways so far.......

- **We should be seeking target platforms with physics gains $G > 100$, and engineering gains $\eta_d G > 10$, that can plausibly be rep-rated at $\lesssim 10$ Hz ($\Rightarrow E_{driver} \lesssim 2$ MJ). $\Rightarrow$ Make the target do the work, not the driver!!**

- **Note that this is for 1000-MWe-class commercial reactors. Target gains of $\lesssim 50$ at $E_{driver} \sim 1$ MJ may suffice of 100-MWe-class engineering test reactors or for multiplexed target chambers driven by a single driver (or for 1000-MWe-class IFE fission-fusion hybrids, but that's another long story)**

- **Even lower gains would suffice for a next-step, high-average-power fusion facility (but it will still likely require rep-rates of $\gtrsim 5$ Hz)***

* Draft requirements for a next-step, high-av.-power fusion facility are discussed below

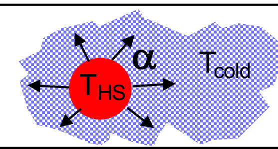
Target physics: High gain targets will *probably* require……

Cryogenic fuel compressed to high density, close to Fermi degenerate (FD) conditions

ρR_α~0.4g/cm^2 req'd (mass=$(4\pi/3)(\rho R)^3/\rho^2$)
If ρ_{DT}=0.25g/cm^3, yield ~10's kilotons
$\Rightarrow$ ρ_{DT} =500g/cm^3, yield ~500MJ

Ignition from a hotspot over a few-% of the fuel mass

Propagating α burn
$\Rightarrow$ T_{HS}~10keV,
$\Rightarrow$ ρR_{HS}~0.4g/cm^2



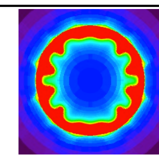
An alpha burn wave propagating into the cold FD fuel mass with adequate inertial confinement

$T_{cold} \lesssim$ 1keV at α_{FD}~1+, $\Rightarrow$ pulse-shaping
$f_{burn\text{-}up}$ ~ρR/(ρR+7) , $\Rightarrow$ ρR~3g/cm^2

This is "just"1-D energy and power dynamics

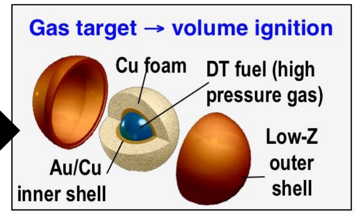
Good symmetry and stability. Low laser-plasma instabilities

- $\Rightarrow$ Convergence ratios $\lesssim$ 35
- $\Rightarrow$ In-flight aspect ratios $\lesssim$ 35
- $\Rightarrow$ $I_{laser}.\lambda^2 \lesssim 10^{14}$ Wcm^{-2}μm^{-2}



This is 3-D with turbulence and GKWE !

This probably precludes room-temperature, high pressure gas targets with volumetric burn
(But gas targets may be a route to ignition and burn at gain ~unity)



The key to higher gain *Part-1*: Low implosion velocity

High target gain requires:

- High ρR, $\Rightarrow$ more fuel burnup
- Low V , $\Rightarrow$ more fuel mass assembled for given driver energy

$$G = \frac{Y_{fusion}}{E_{driver}} = \frac{Y_{fusion}}{\frac{1}{2} m_{fuel} V^2 / \eta} \sim \frac{\rho R / (\rho R + 7)}{V^{1.3}}$$

Ref. 1

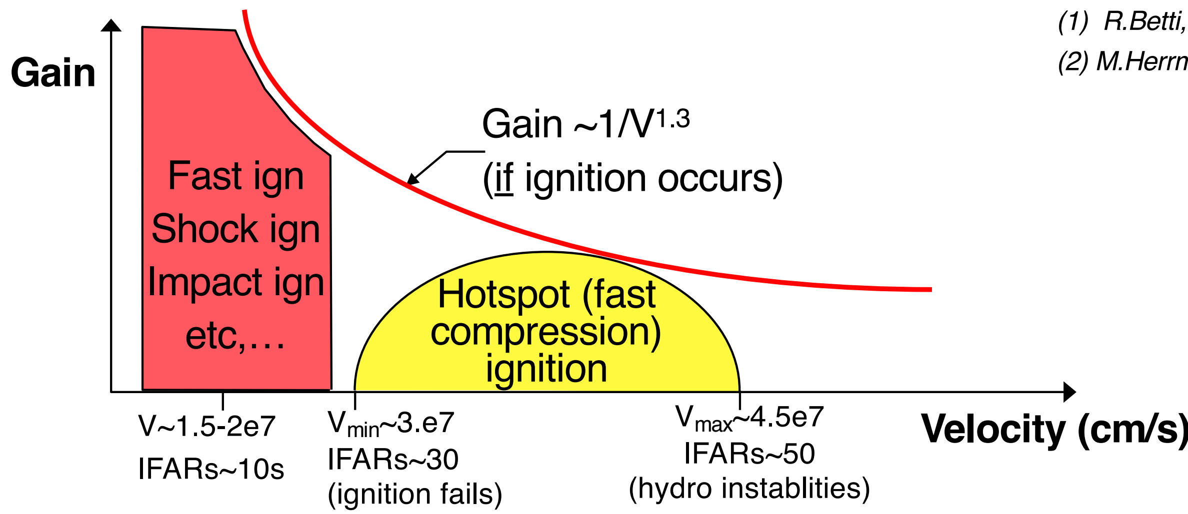
But "hotspot" (= fast-compression) ignition needs high velocity to minimize ignition energy

$$E_{ign-req'd} \sim \frac{\alpha_{FD}^{1.8}}{V^6}$$

Ref. 2

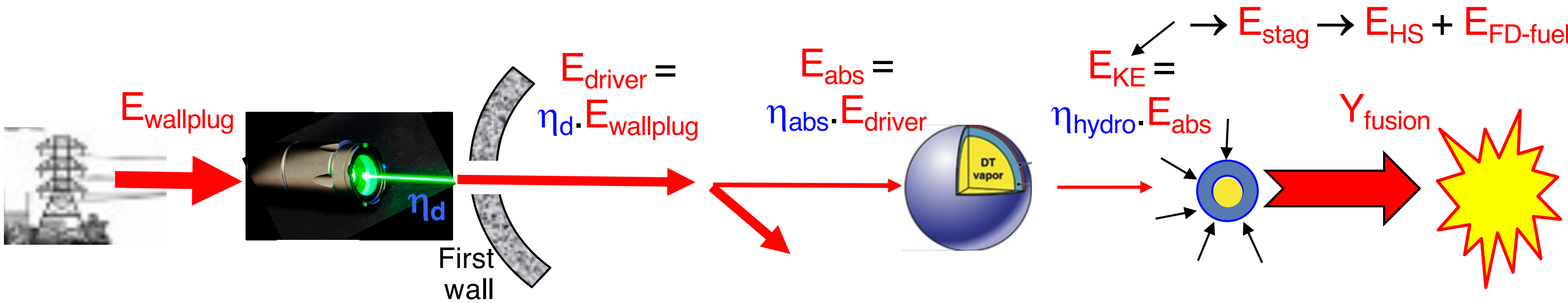
(1) R.Betti,, Phys Plasmas (2005)

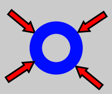
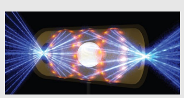
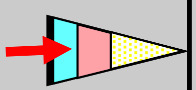
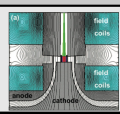
(2) M.Herrmann. Phys Plasmas (2001)



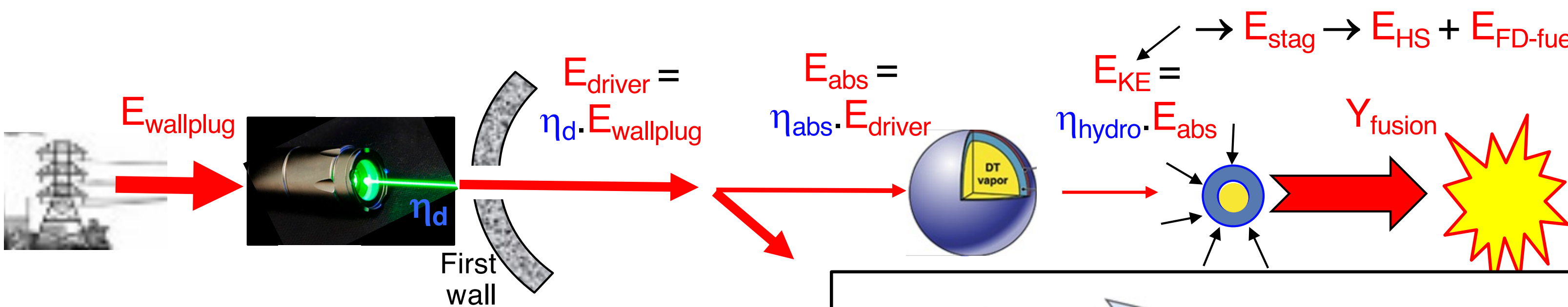
R.Betti (2008)

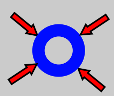
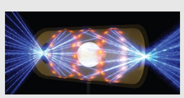
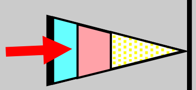
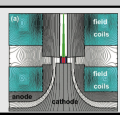
The key to higher gain *Part-2*: High driver-target coupling efficiencies

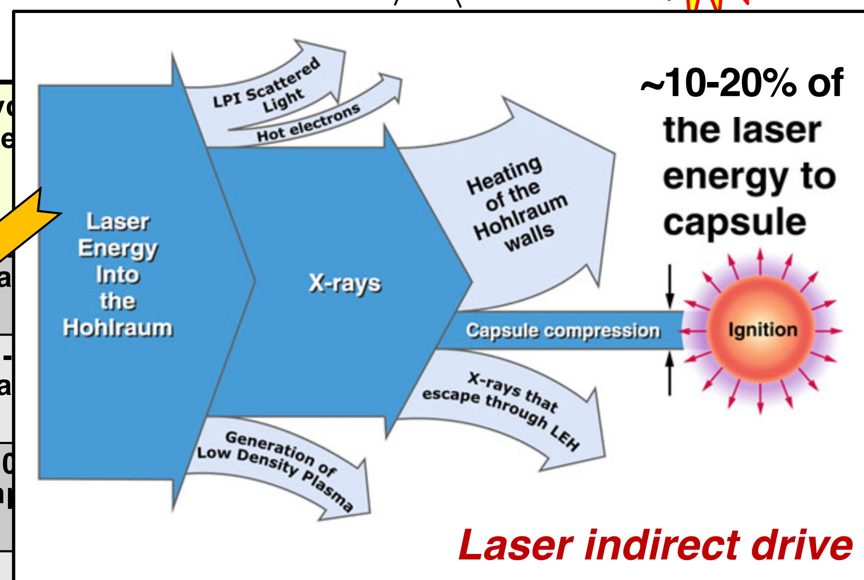


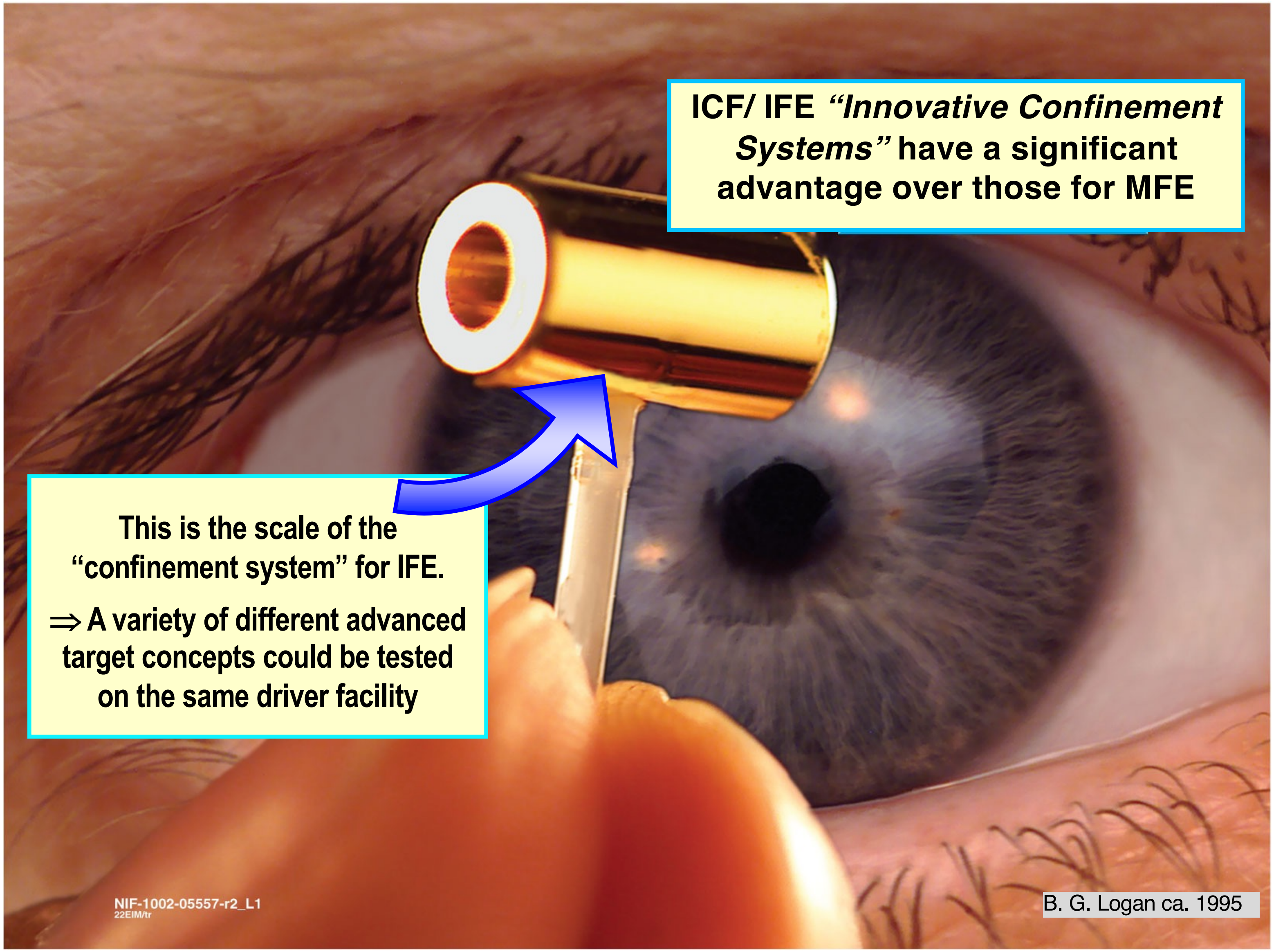
	Driver electrical efficiency η_d	Absorption efficiency η_{abs}	Hydro (rocket) efficiency η_{hydro}	System drive efficiency $E_{wallplug} \rightarrow E_{KE} = \eta_d \cdot \eta_{abs} \cdot \eta_{hydro}$
Laser direct 	~0.05-0.20	~0.65-0.85 (PDD-SDD)	~0.06-0.1 (ablative)	~0.01
Laser indirect 	~0.05-0.20	~0.1-0.2	~0.1-0.15 (ablative)	~0.005
Heavy ion direct 	~0.25-0.40	~0.9	~0.20 (tamped ablative)	~0.05
Pulsed power direct 	~0.3	~0.2 - 0.3 (direct magnetic)		~0.05

Laser indirect drive: Where does the energy go?

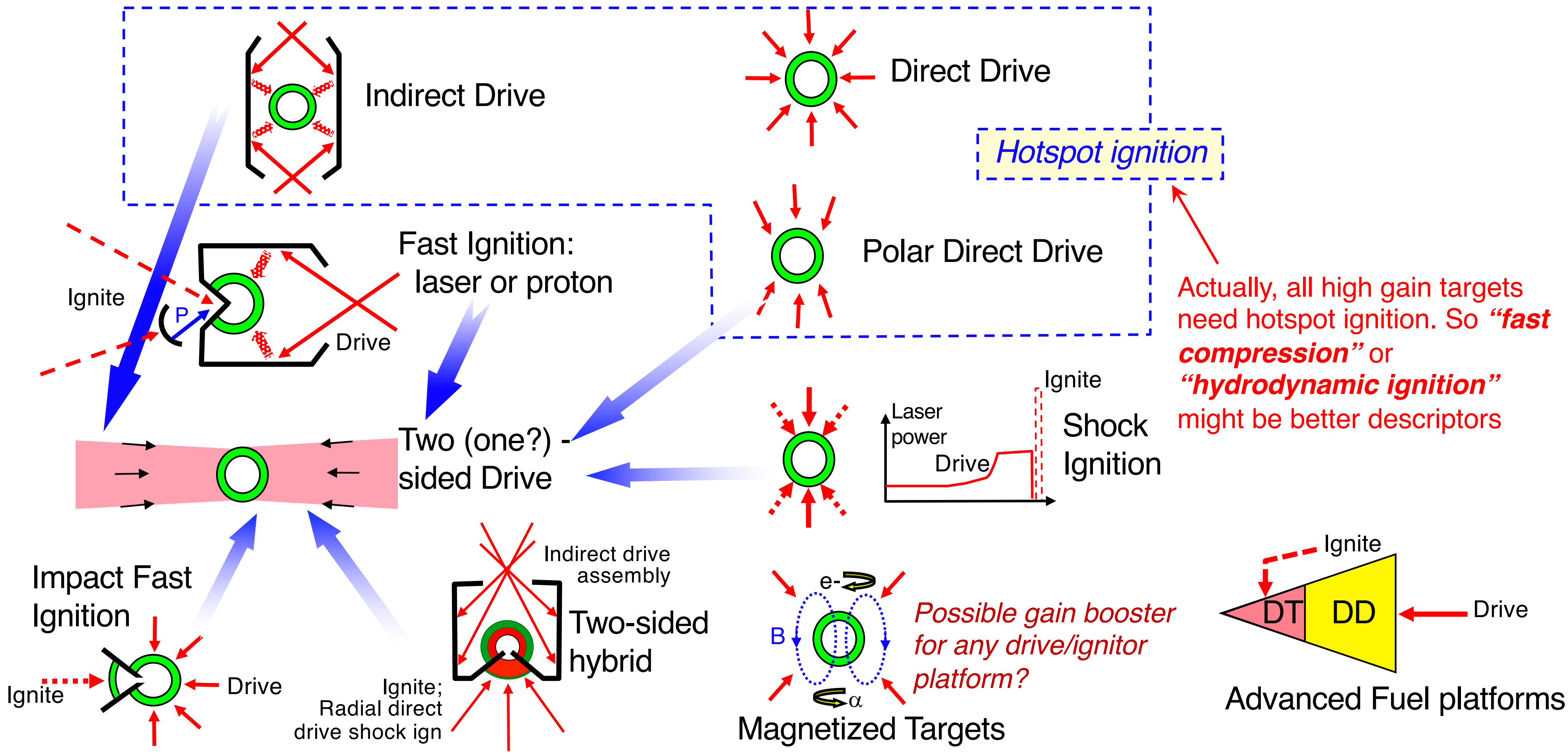


	Driver electrical efficiency η_d	Absorption efficiency η_{abs}	Hy… e…	
Laser direct 	~0.05-0.20	~0.65-0.85 (PDD-SDD)	~0… …bla…	
Laser indirect 	~0.05-0.20	~0.1-0.2	~0.1- (abla…	
Heavy ion direct 	~0.25-0.40	~0.9	~0.20 (tamp…	
Pulsed power direct 	~0.3	~0.2 - 0.3 (direct magnetic)		

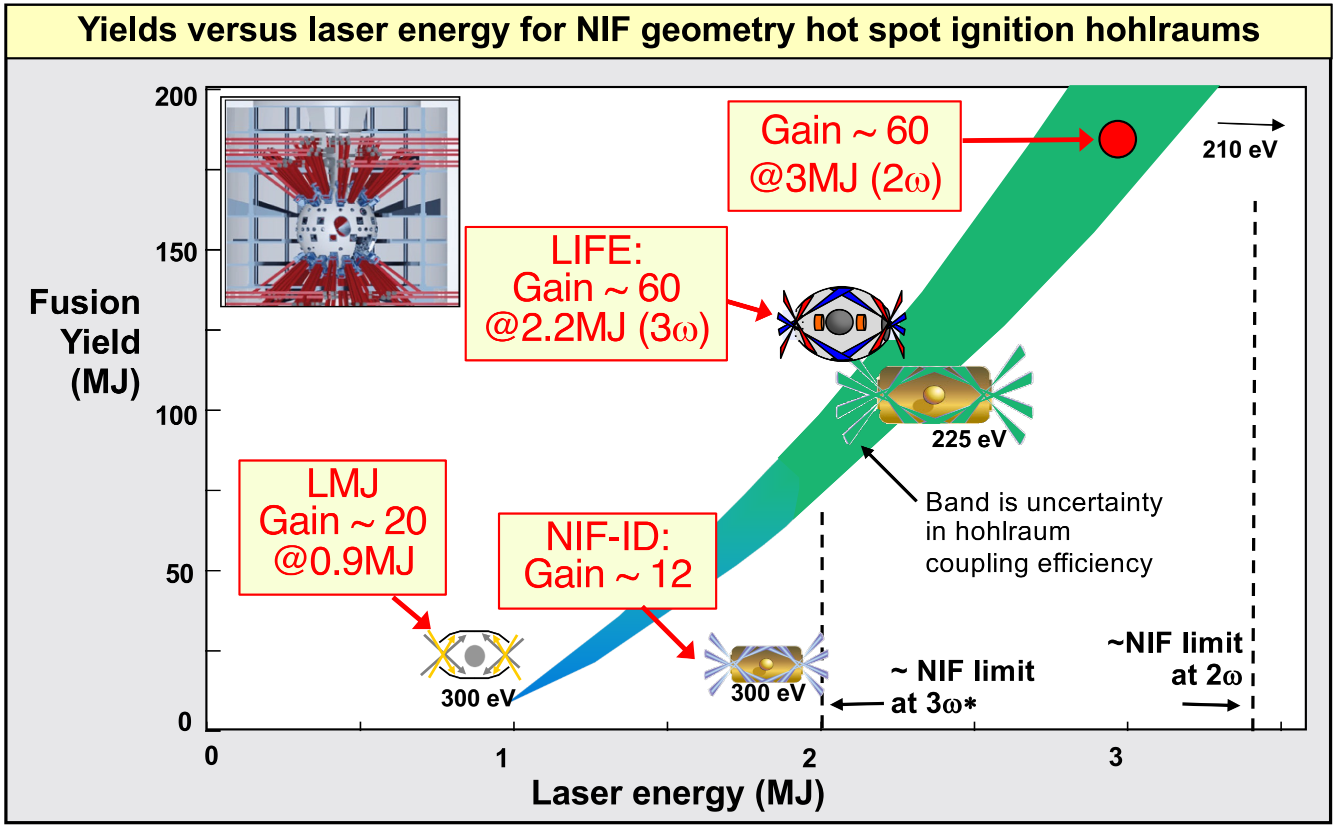



ICF/ IFE *"Innovative Confinement Systems"* have a significant advantage over those for MFE
This is the scale of the "confinement system" for IFE.
⇒ A variety of different advanced target concepts could be tested on the same driver facility
NIF-1002-05557-r2_L1
22EIM/tr
B. G. Logan ca. 1995

A survey of advanced (laser) targets – Could they be tested on NIF at gain and yield ? (or LMJ?)



Indirect Drive (hotspot ignition) in NIF geometry is enabling for researching IFE applications

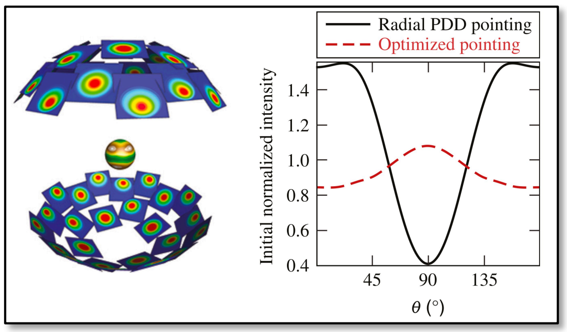


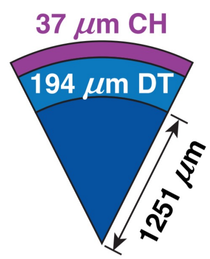
J.Lindl 2007; P.Amendt 2011; Lafitte 2010; Updates 2021

** ~2MJ (2021); ~2.2MJ (2023)*

Direct Drive (hotspot ignition): LLE's NIF PDD designs predict gains ~40 when CBET is mitigated via expanded wavelength detuning

NIF Polar Direct Drive Designs *(Collins, 2018)*





*T.Collins and J.Morozas, POP **25**, 072706 (2018)*

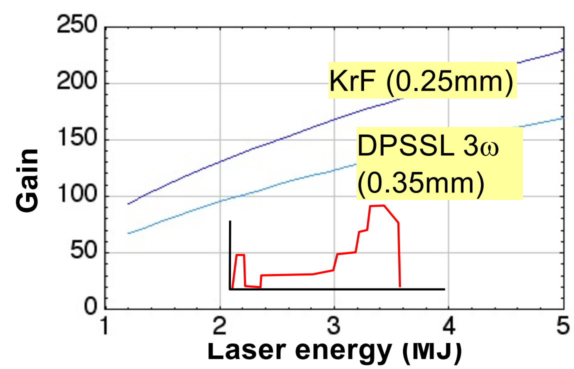
	High gain α = 2.8	Robust alpha-burning design α = 4.8
Drive energy (MJ)	1.8	1.8
Yield (MJ)	74	0.41
Gain	41	0.23
V (cm/s)	4.0e7	3.9e7
IFAR	23	20
CR	28	25
Peak ρR (g/cm^2)	1.7	1.4

Laser abs. efficiency = 72%

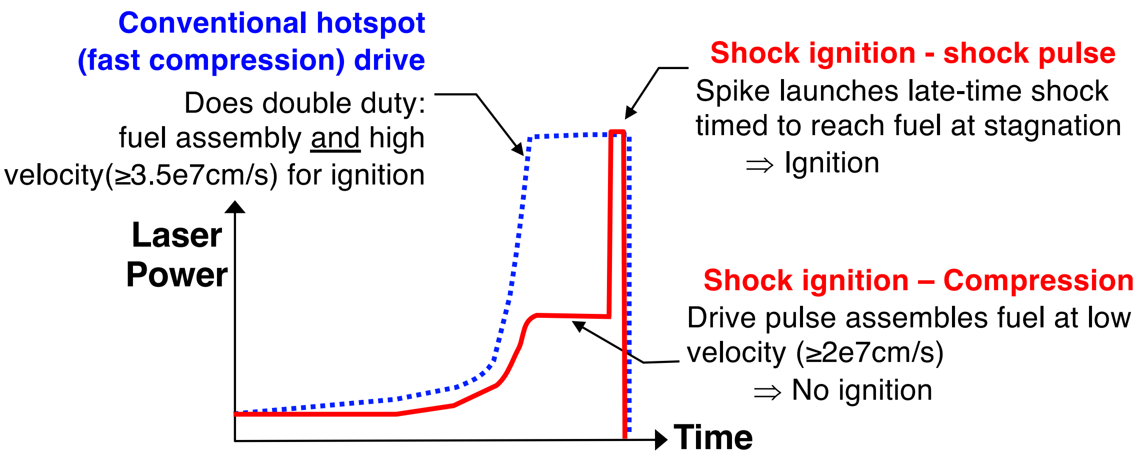
(~ 83% in symm. DD)

Symmetric Direct Drive Simulations for the High Average Power Laser Program *(2010)*
Gain >100@2MJ w/ KrF and zooming

*Sethian et al. IEEE Trans Plas Sci **38**, 690 (2010)*



Shock-Ignition*: Implode at low velocity and ignite separately



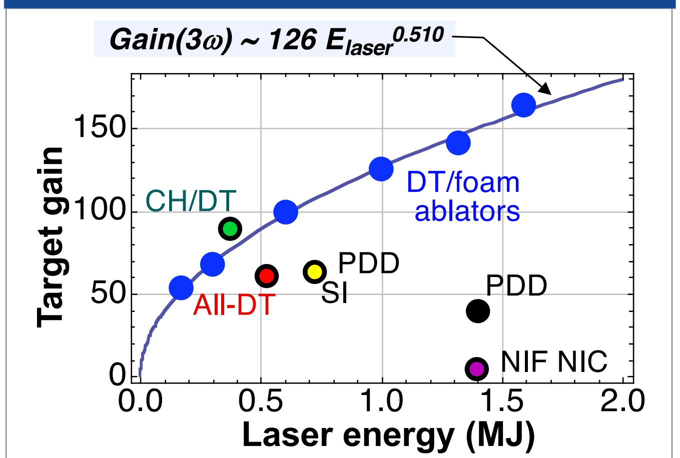
$E_{laser} \rightarrow E_{fuel,\ max\ KE}$

$\sim 1/2\ m_{fuel} V^2$

high low

- Higher gain/yield for a given laser drive energy
- Relative to “fast-ignition” :
  - Time/spatial requirements less stringent (~ x10)
  - Uses same laser (no separate short pulse laser req’d)
  - Process modeling is (more or less) standard hydro
  - ***But*** *(a)* conventional symmetry/stability constraints apply, and (b) may only be feasible in direct drive

NIF Shock Ignition Gain Curve (symm.)

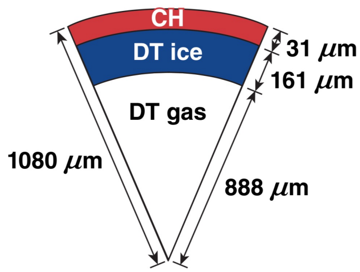


*L. J. Perkins et al., Phys Rev Lett **103** 045004 (2009)*
K.Anderson, 54th APS DPP (2012)

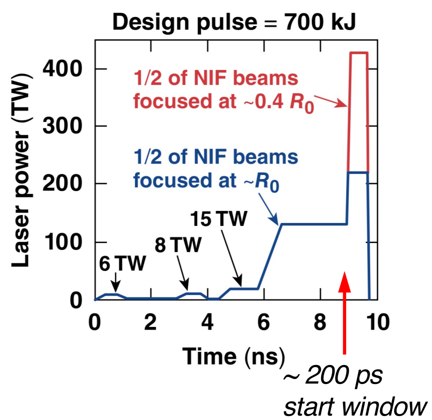
*R.Betti et al., Phys Rev Lett **98**, 155001(2007)*

Shock-ignition – A polar-direct-drive shock-ignition target has been designed for NIF at 700 kJ with gain ~60

NIF PDD high gain shock ignition design *(Anderson 2012)*

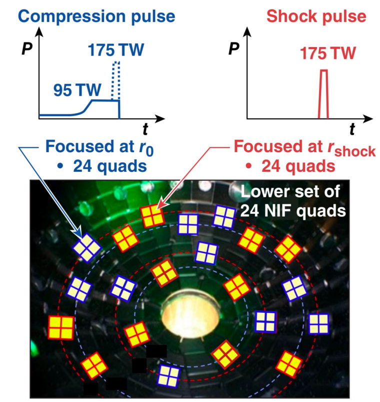


Gain (1-D)	58
ρR (g/cm^2)	1.6
V_{imp} (μm/ns)	305
IFAR$_{2/3}$	22
Average adiabat	1.8
ITF	4.1



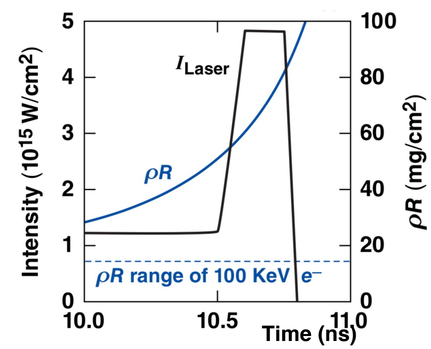
K.Anderson, 54th APS DPP (2012)

NIF PDD SI designs could employ split focusing with half the beams each dedicated to compression and shock



PDD laser coupling expts on NIF at high intensity

- ~15% intensity reduction due to CBET at 1x10^{15} and 2.5x10^{15} W/cm^2
- Shock trajectories not strongly influenced by hot electrons observed in the experiments



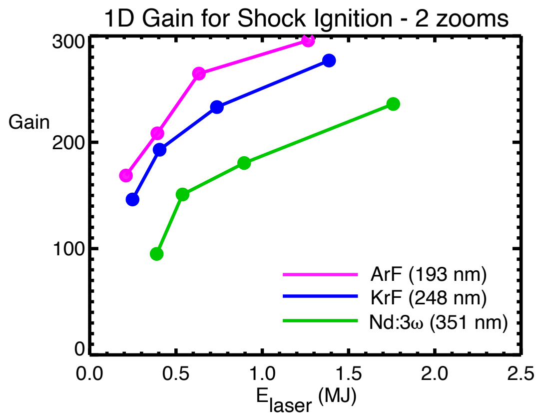
At moderate energy, hot electrons are stopped in the dense ablator and may aid shock pressure

K.Anderson, 62nd APS DPP (2020)

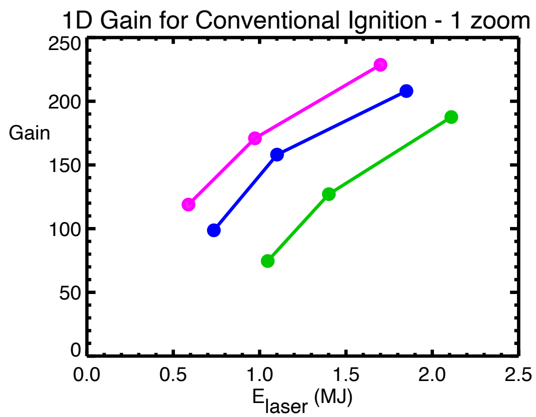
*R.Betti, J. Phys Con Ser **112**, 022024 (2008)*

Shock-ignition – Where did that gain-200 @ 1 MJ design point come from?

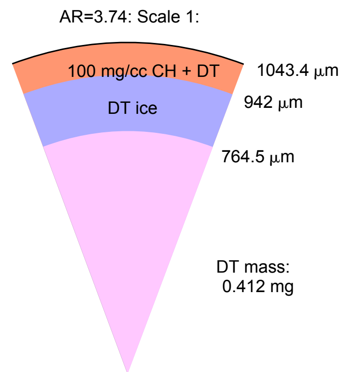
Enabled by ArF, KrF attributes: *Shorter UV wavelength, higher bandwidth, "zoomed" focal profile, higher threshold for laser plasma instability (and symmetric drive)*

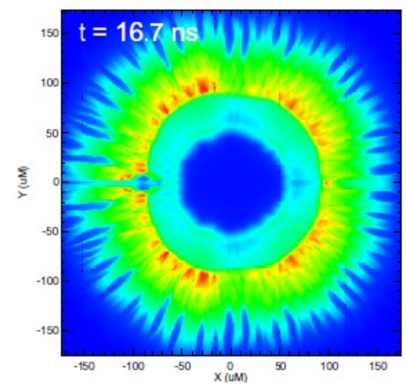


Shock ignition
Gain ~200 at 1MJ



Conventional Ignition
Gain ~150 at 2MJ

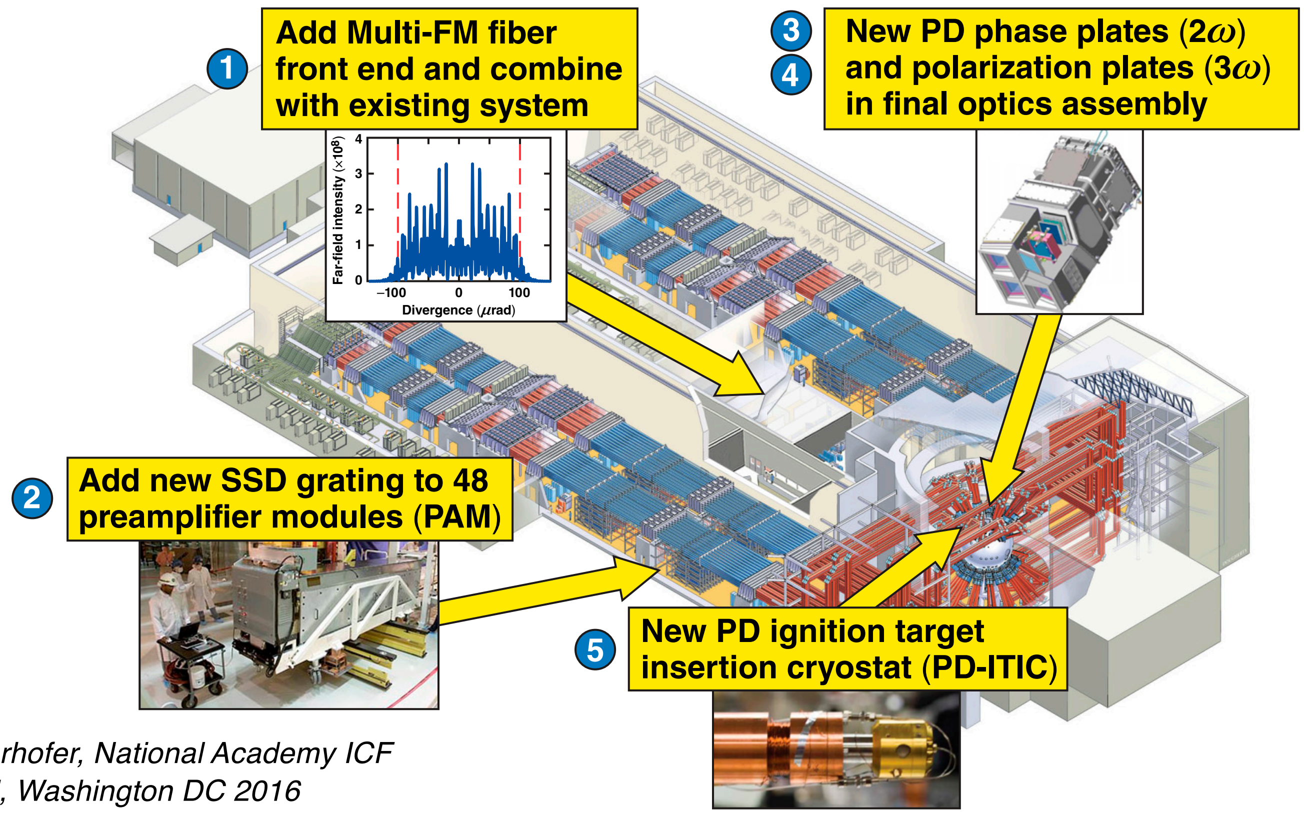




Realistic 2D simulations typically give ~70% of the 1D gain.
(in symm direct drive)

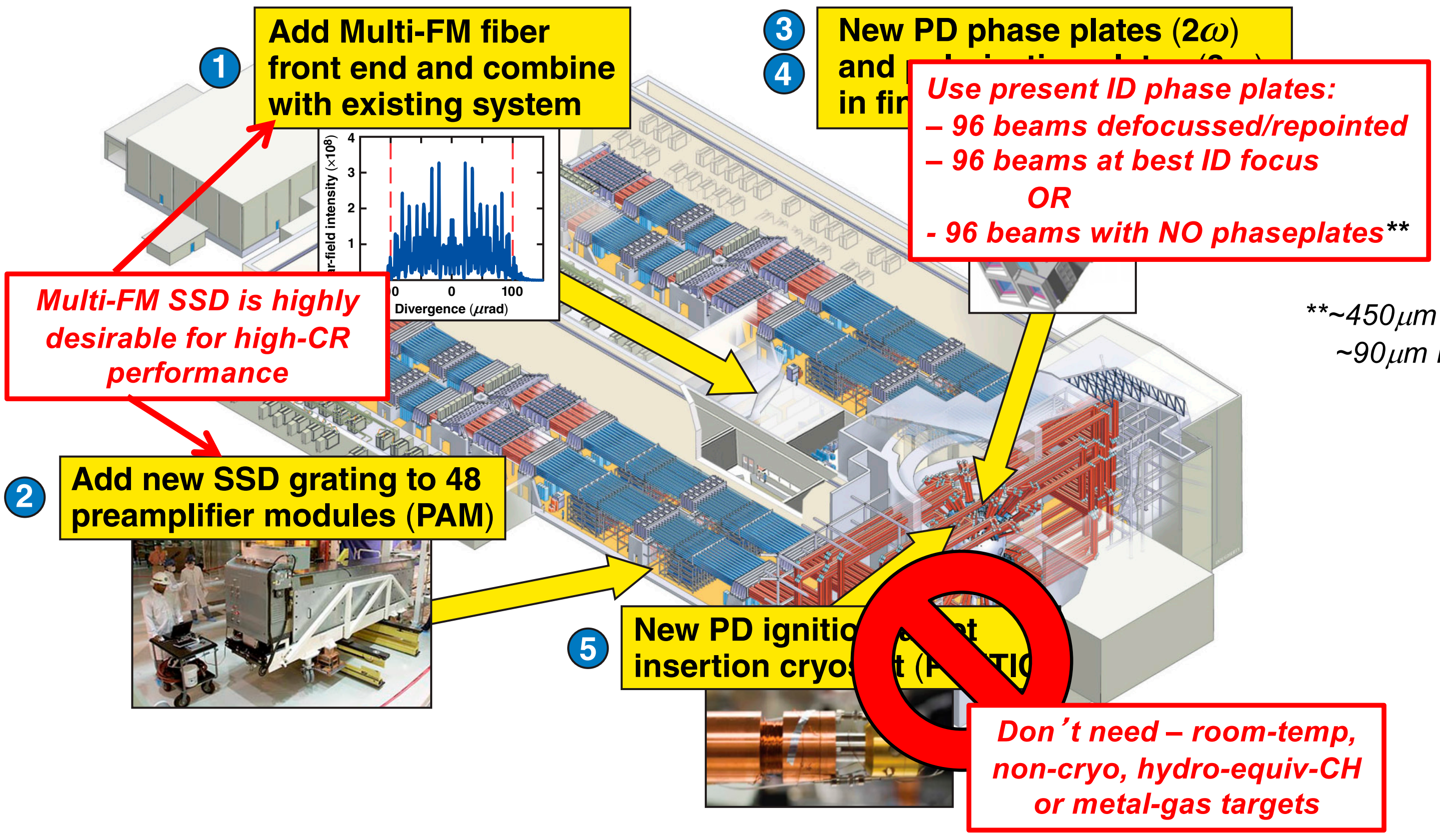
A. Schmitt, NRL (2021)

Full implementation of NIF polar direct drive – regular or shock ignition – will require five hardware upgrades for a (cryo) ignition demonstration



R.McCrory, D.Meyerhofer, National Academy ICF Target Panel, Washington DC 2016

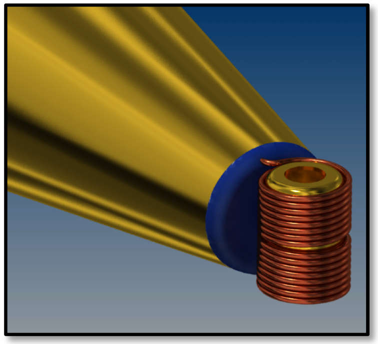
Might shock ignition validation experiments be fieldable with ~present hardware and non-cryo, hydro-equivalent CH or metal-gas platforms? (2014 perspective*)

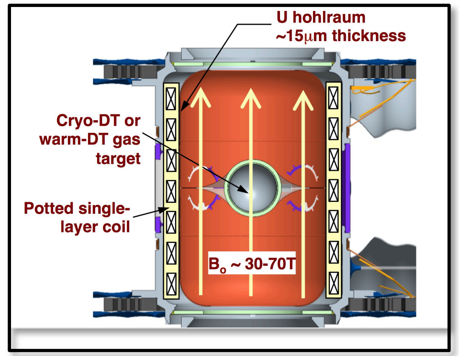


**~450μm @ CPP best focus
~90μm no phaseplates

*2014 scoping studies, L. J. Perkins, R. Betti, K. Anderson, S.Craxton

Magnetized targets: Potential gain/yield boosters for any platform?

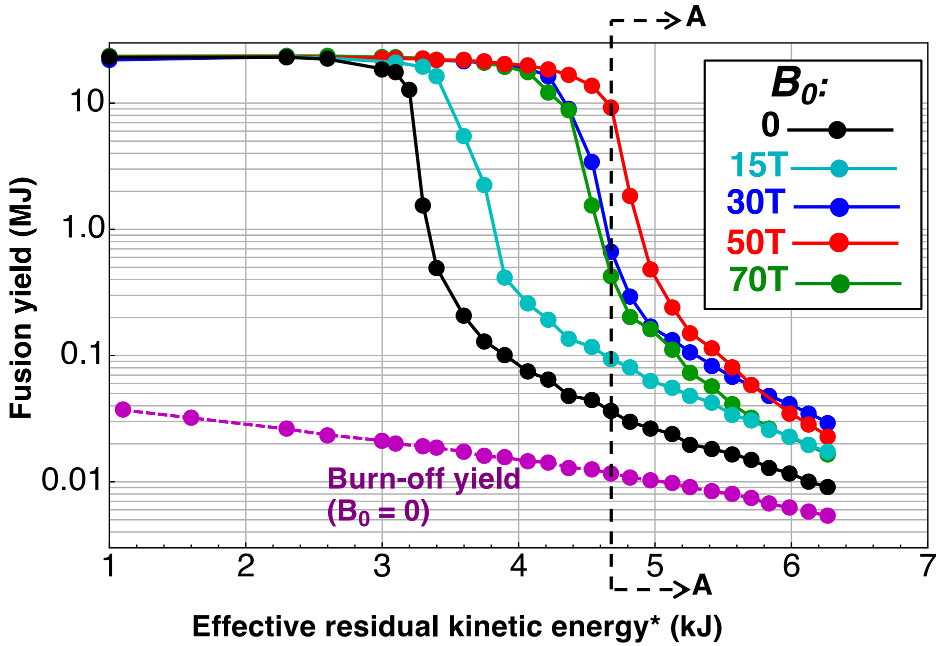


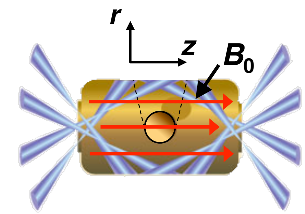


- Initial fields of 20-50T compressing to >10^4 T (100's MG) under implosion may relax stagnation conditions for ignition and thermonuclear burn in *standard* NIF targets (indirect-drive cryo hotspot-ignition and volumetric-ignition metal-gas target variants)
- Trapped alpha particles are localized within hotspot; electron heat conduction loss in hotspot is shut off across the field ($\omega_{ce}\tau_{ei}$>>1) As might frozen-in "closed" field lines spun up by residual-KE. => Can reduce required hotspot ρR*T and pressure for ignition leading to higher gains/yields
- Compressed field may suppress Rayleigh-Taylor instability ingress into hotspot during stagnation
- Imposed magnetic fields may enable volumetric ignition/burn in room-temperature high-Z metal-gas targets and may enhanced gas yields in room-temperature low-Z platforms (first experiments?)
- Hohlraum field may improve inner beam propagation and may inhibit transport of late-time LPI hot electron preheat to capsule

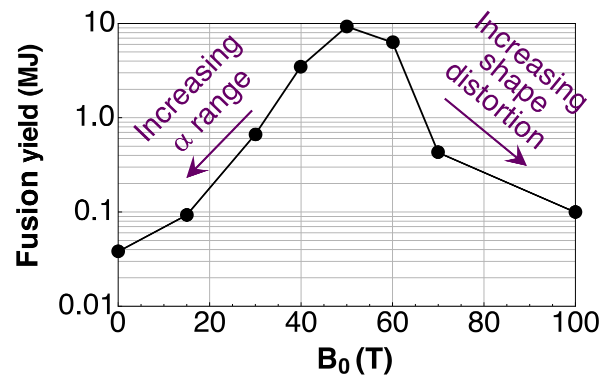
Magnetized targets: Optimum imposed fields are a few-10's of Teslas

The optimum imposed field is around 50T





Scan -v- B_0 across A-A

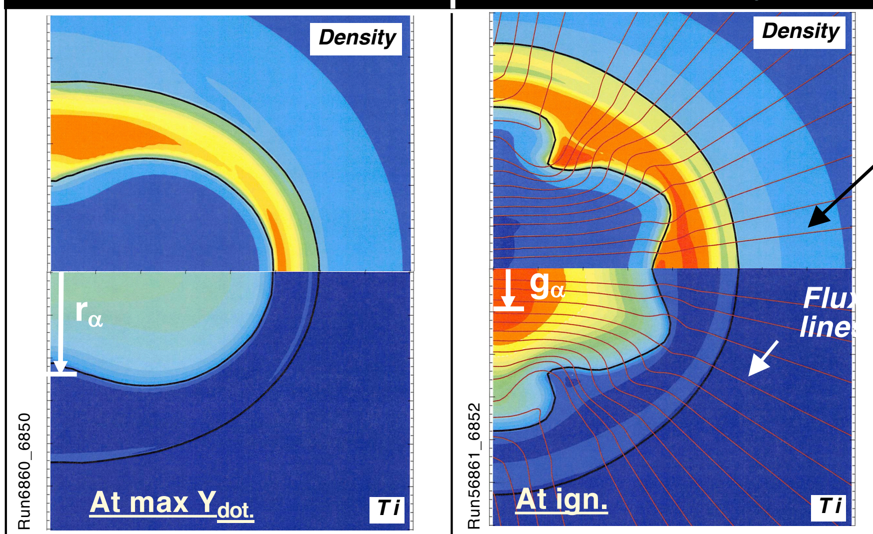


L. J. Perkins, POP, 24, 062708 (2017)

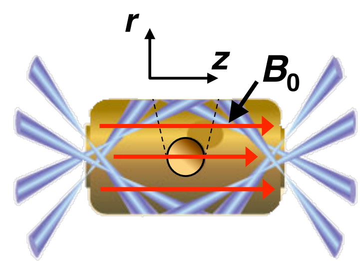
Magnetized targets: Application of imposed B-field of 50T to a submarginal capsule at the bottom of the ignition cliff may induce ignition and high yield

Hotspots at stagnation.

These are the same capsules with same perturbations and same inflight conditions!



Flux lines.
$<B_{HS}> = 5.2*10^4$T
(520Mgauss)

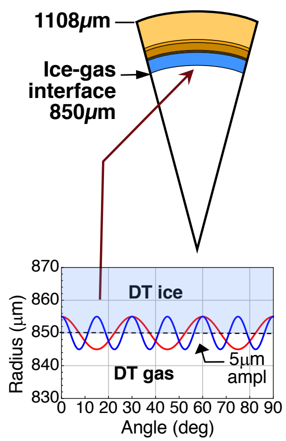


	2D Perturbed. No B	2D Perturbed. B_0=50T
Fusion yield (MJ)	0.036 ($1.3*10^{16}$ n)	9.28 ($3.3*10^{18}$ n)
T_{i_Brysk} (keV)	3.80	17.9
ρR_{shell}	1.38 (σ_{RMS} = ±51%)	1.27(σ_{RMS} = ±26%)
Conv. ratio	33.0	31.6
Burn off:		
Yield (kJ)	11.7	17.3
T_{i_Brysk} (keV)	3.23	3.65
P_{hs} (Gbar) max, burn-av.	221, 164	260, 191

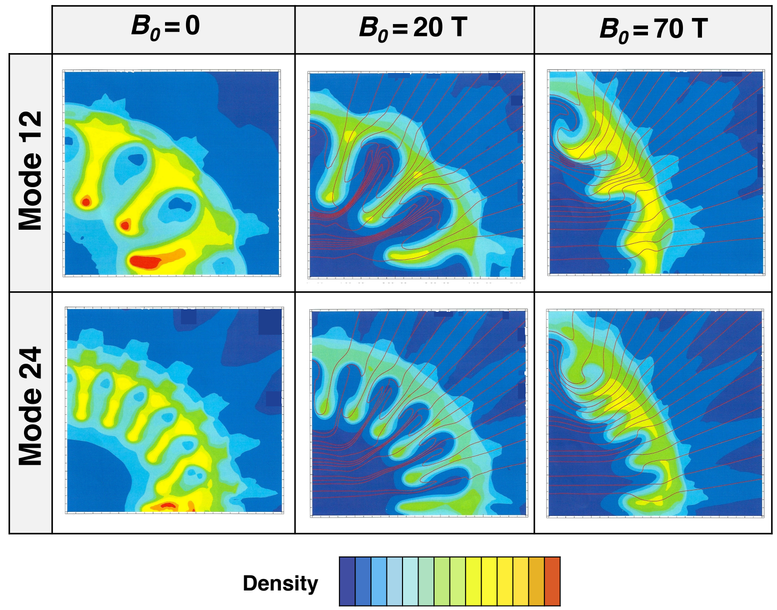
L. J. Perkins, POP, 24, 062708 (2017)

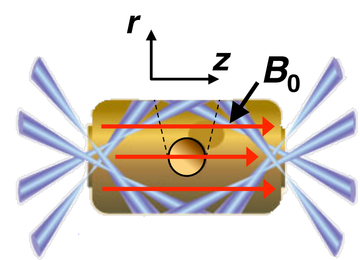
Magnetized targets: Simulations indicate that RT-growth into the hotspot may be suppressed at higher B-fields

Density contours in the r-z plane at ignition (T(0)=12keV) for imposed single-mode perturbation of amplitude 5μm on ice-gas interface at t=0



5μm amplitude
ℓ=12 and ℓ=24 cosine
initial perturbation on
ice-gas interface at t=0





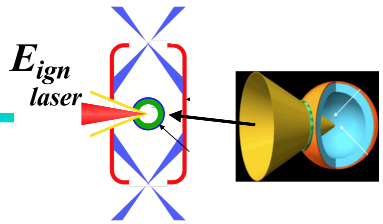
J. Perkins, POP, 24, 062708 (2017)

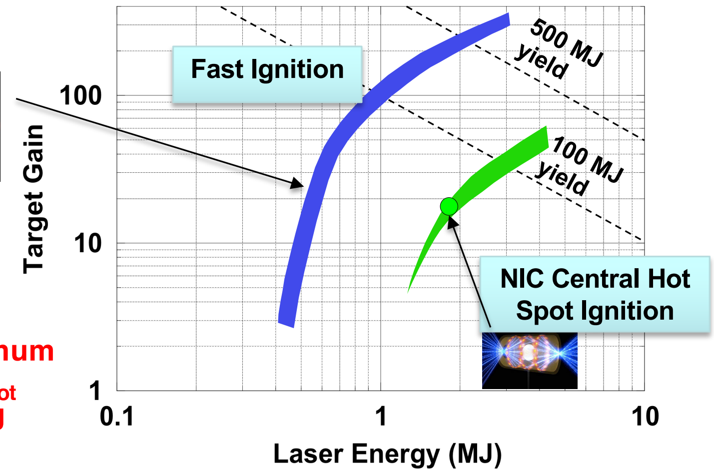
Suppression of RT instabilities is due to the field-line bending energy that must be expended (good curvature direction → stabilizing).

Effect will be enhanced at higher mode numbers (smaller bend radii) but 3-D simulations will be required for full insight

Fast Ignition: Decouple compression from ignition (and could alleviate conventional symmetry/stability constraints)

Fast ignition offers potential target gains of ~100 at 1MJ



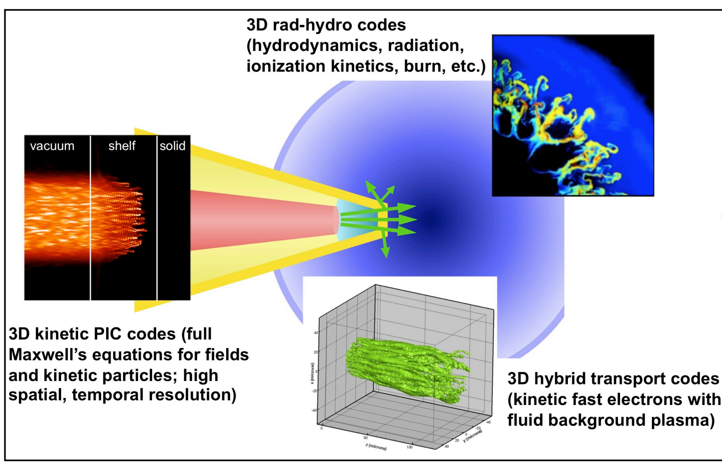


≳0.5g/cm²

~10keV

$$E_{ign\ laser} \sim \frac{1}{f_{coupled}} \left[\frac{(\rho r)^3_{hot} T_{hot}}{\rho^2} \right]$$

minimum $E_{hotspot}$ ~15kJ



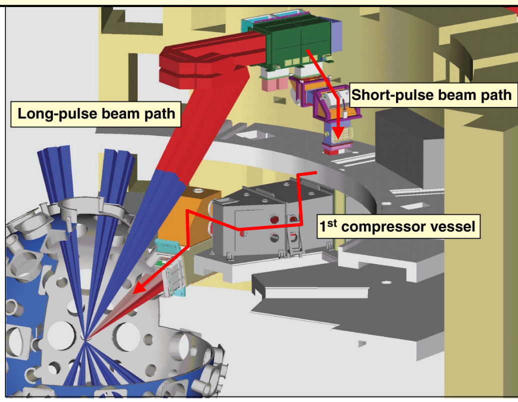
FI target design:
Conventional ICF (rad-hydro) plus relativistic laser-plasma interactions (kinetic-PIC)

⇒ Rich (and complex) multi-scale physics

P.Patel et al 2010

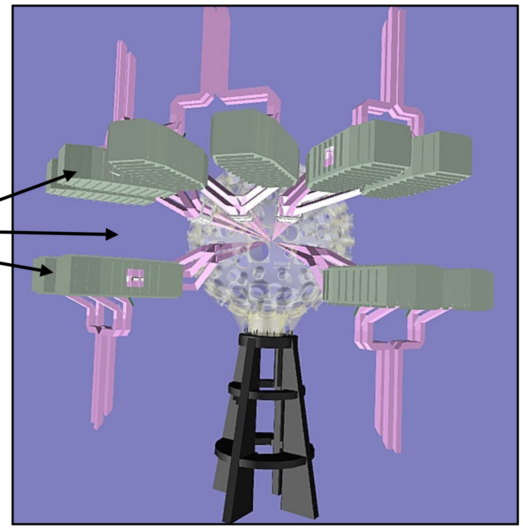
Fast ignition on NIF: Options for FI coupling experiments at full hydro scale

Advanced Radiography Capability (ARC) applied to FI energy channeling: Measure FI coupling efficiency at full hydro scale



NIF might possibly adapted for ~30kJ of short pulse energy

5 quads
20 beams
20ps CPA,
1ω~60kJ



ARC today (2021):

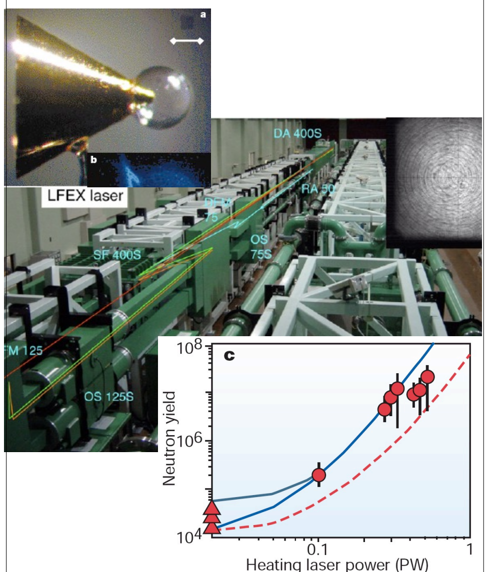
- 4 kJ (1ω) from ½-quad = 4-beamlets
- ~20 ps; ≥150-μm-spot
- Potentially 8 kJ, 1-quad = 8-beamlets (≥ 2023, if you can make a case)

Preliminary integrated target simulations suggest that high-gain fast ignition on NIF may require ~150-200kJ of short pulse energy (⇒ new laser?)

Patel et al ≥2010

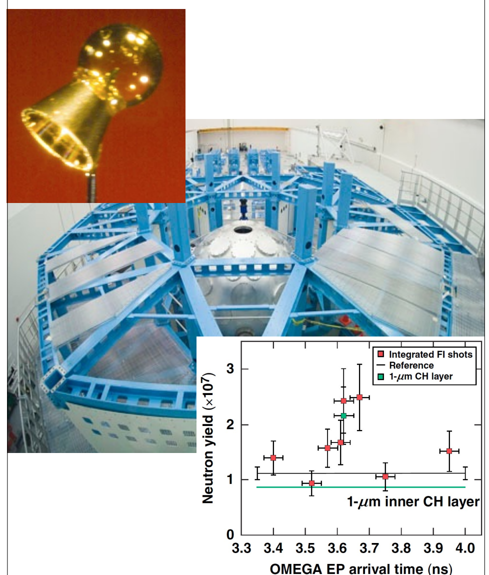
Fast ignition: Integrated compression/core heating experiments must validate key coupling physics prior to a fast ignition demonstration – Part 1

FIREX *(ILE Osaka)*



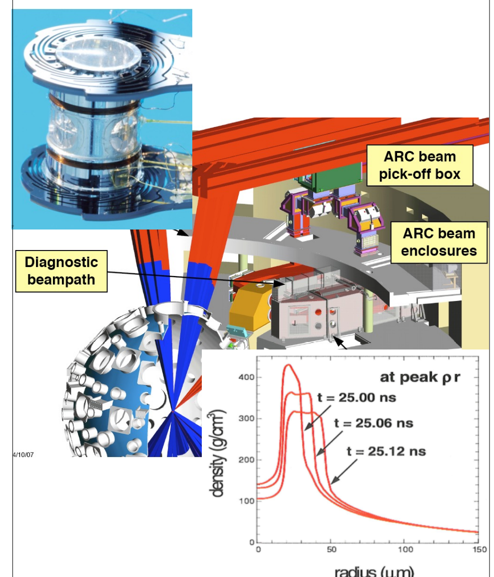
10 kJ, 2ω compression, ~2 kJ, 10 ps ignitor

OMEGA / EP *(LLE, Roch.)*



30 kJ, 3ω compression, 2.6 kJ, 10 ps ignitor

NIF ARC *(LLNL)*



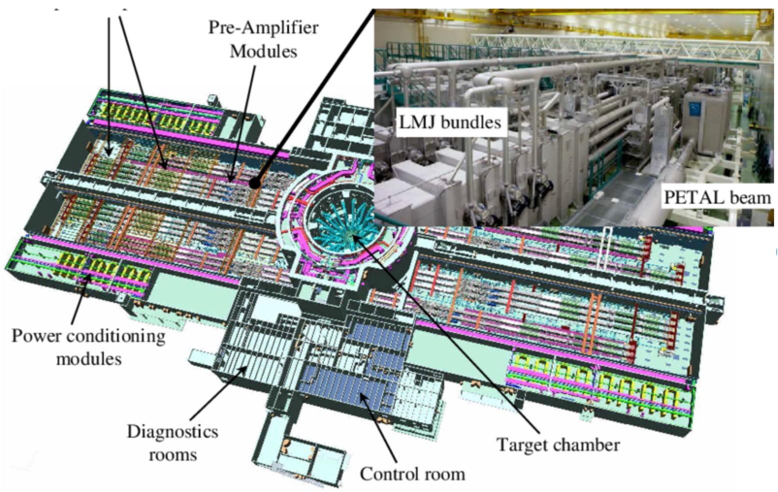
1.7 MJ, 3ω compression, 8 kJ, 20 ps ignitor

Continued over……

Patel 2012; updated 2021

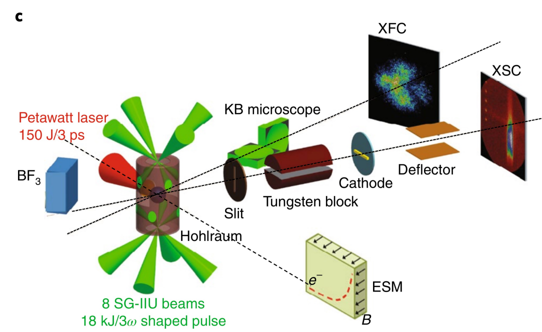
Fast ignition: Integrated compression/core heating experiments must validate key coupling physics prior to a fast ignition demonstration – Part 2

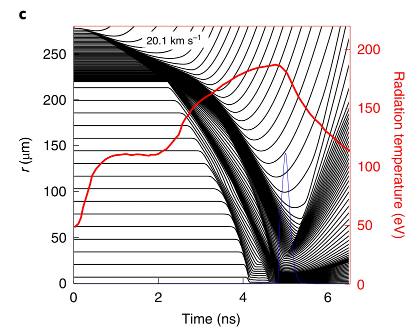
LMJ / Petel *(CEA Bordeau)*



600 kJ, 3ω compression,
5 kJ, 10 ps ignitor

SG-IIU *(Mianyang China)*





ARTICLES
https://doi.org/10.1038/s41567-020-0878-9
nature physics
Check for updates

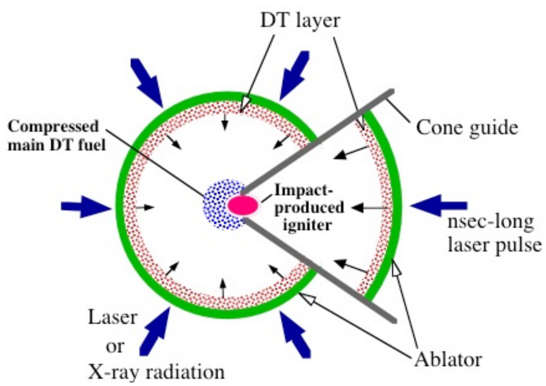
Enhanced energy coupling for indirect-drive fast-ignition fusion targets

F. Zhang[1,7], H. B. Cai[2,3,7]✉, W. M. Zhou[1], Z. S. Dai[2], L. Q. Shan[1], H. Xu[4], J. B. Chen[1], F. J. Ge[2],
Q. Tang[1], W. S. Zhang[2], L. Wei[1], D. X. Liu[1], J. F. Gu[2], H. B. Du[1], B. Bi[1], S. Z. Wu[5], J. Li[1], F. Lu[1], H. Zhang[5],

18 kJ, 3ω compression (8 SG-II beams)
150 J, 3 ps ignitor

Updated 2021

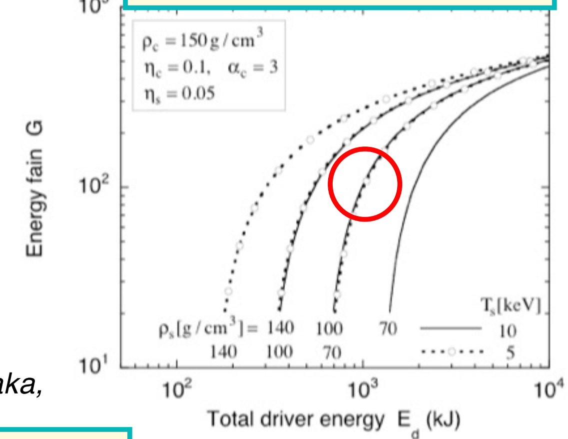
Impact (fast) ignition predicts gains >100 at 1MJ (and like fast ignition may alleviate symmetry/stability constraints)



Impactor - Requirement for Ignition

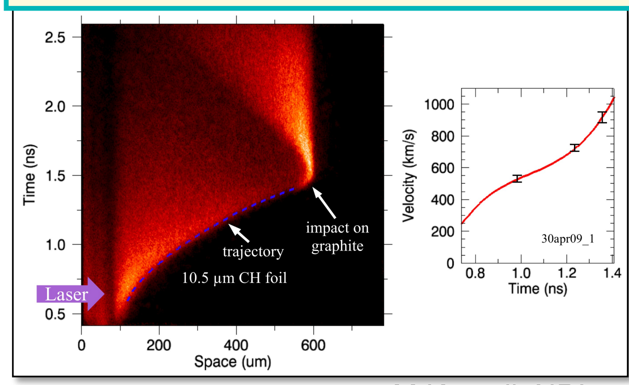
- Kinetic energy → Thermal energy
  1/2 m.v^2 → 2nkT (T~10keV)
  ⇒v = ~10^{8}cm/s
- Momentum→ stagnation pressure
  $\rho . v^2 \to P_{core}$
  ($P_{core} = 2.2\alpha\rho_{core}^{5/3}$, $\alpha = 3$, $\rho_{core} = 200$ g/cc)
  ⇒ρ = 5 g/cc

Projected gain curves



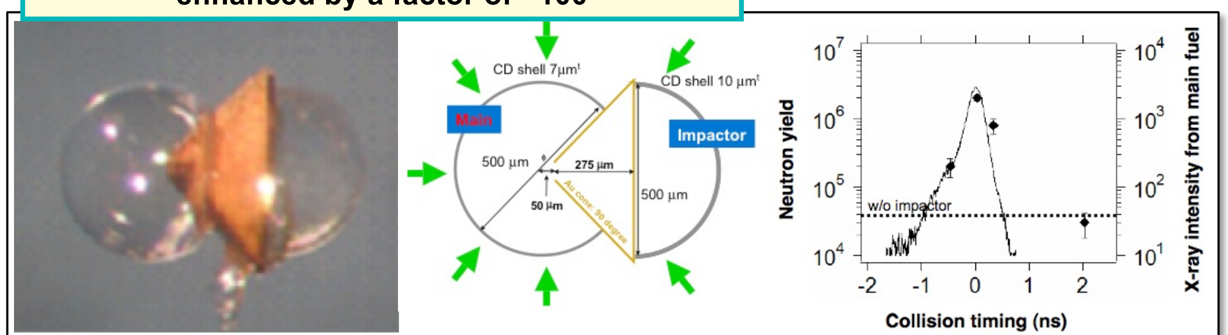
M.Murakami ILE/Osaka,

~10^{8}cm/s flyer plate velocities have been obtained experimentally @ NIKE (NRL)

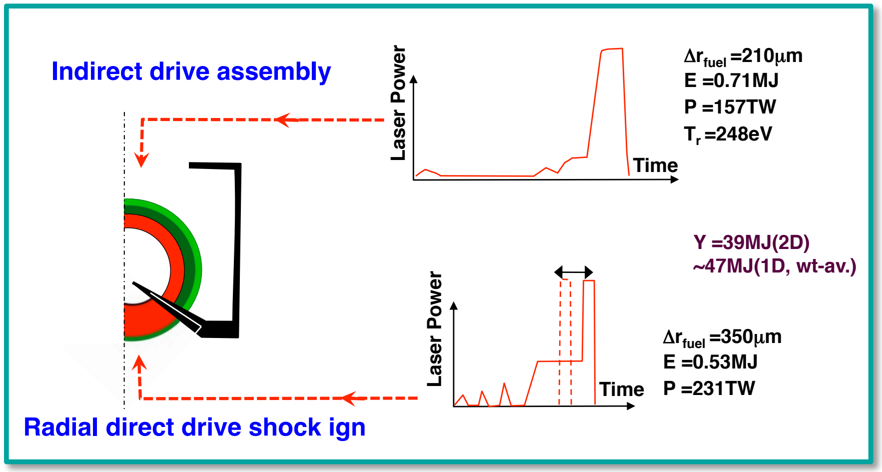


M.Karasik NRL

With impact drive, neutron yields have been enhanced by a factor of ~100



Two-sided hybrid target: A potential nearer term route to shock ignition without polar direct drive or new phaseplates ?



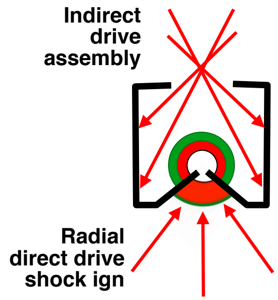
L. J. Perkins
US Patent: US-9905318 B2 (2018)

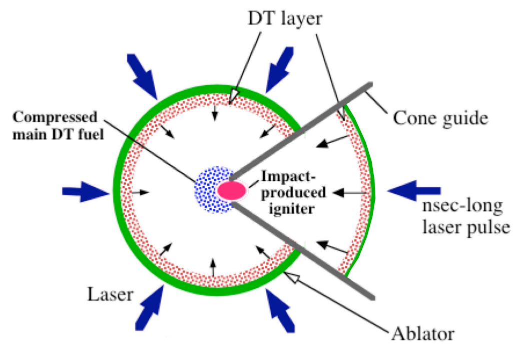
An indirect/direct-drive two-sided hybrid potentially offers:

– The symmetry advantages of indirect-drive for fuel assembly together with the efficiency of radial-direct-drive shock ignition in a capsule with thick fuel layers

– A possible nearer term route to shock ignition on NIF because it obviates the need for a polar direct drive qualification campaign, new phaseplates (may only need multi-FM 1D SSD and only on the lower 24-quads) and should minimize cross-beam energy transfer

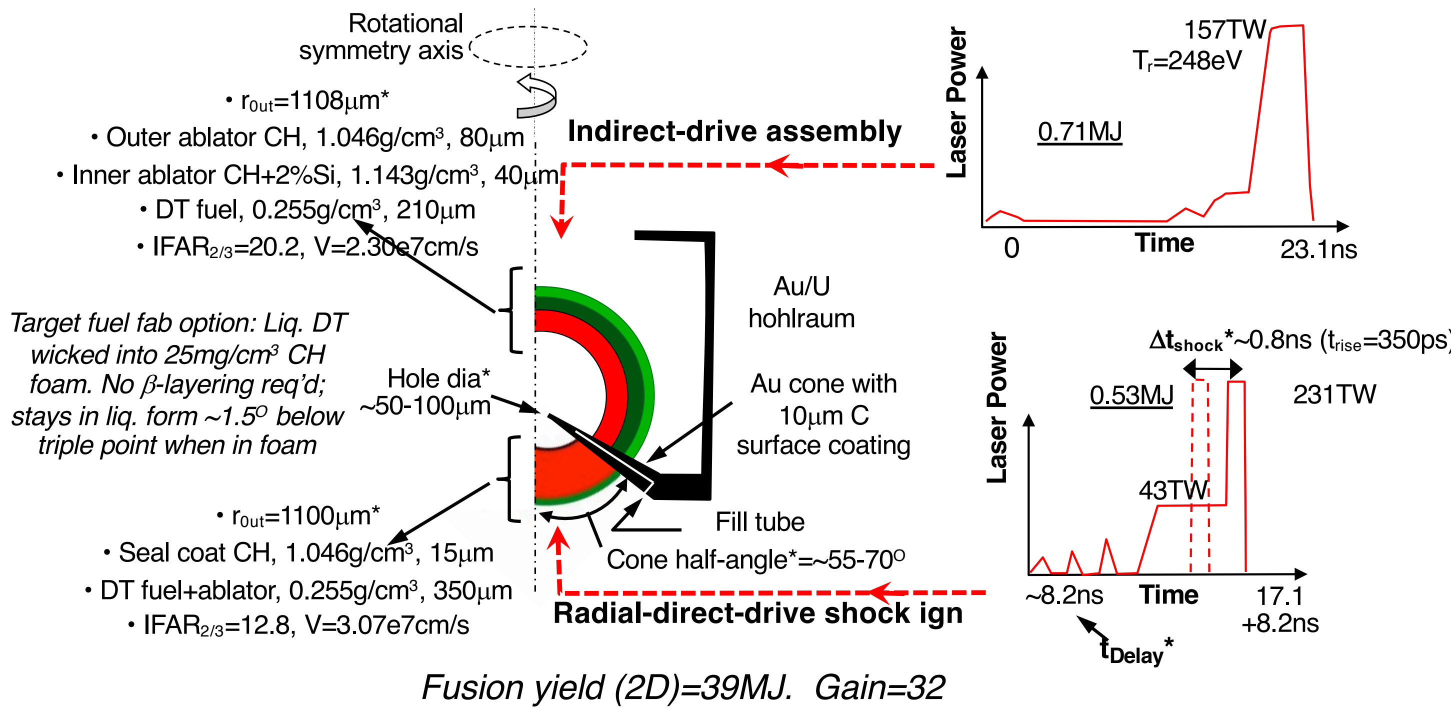
Two-sided hybrid target: How is this different from impact fast ignition?





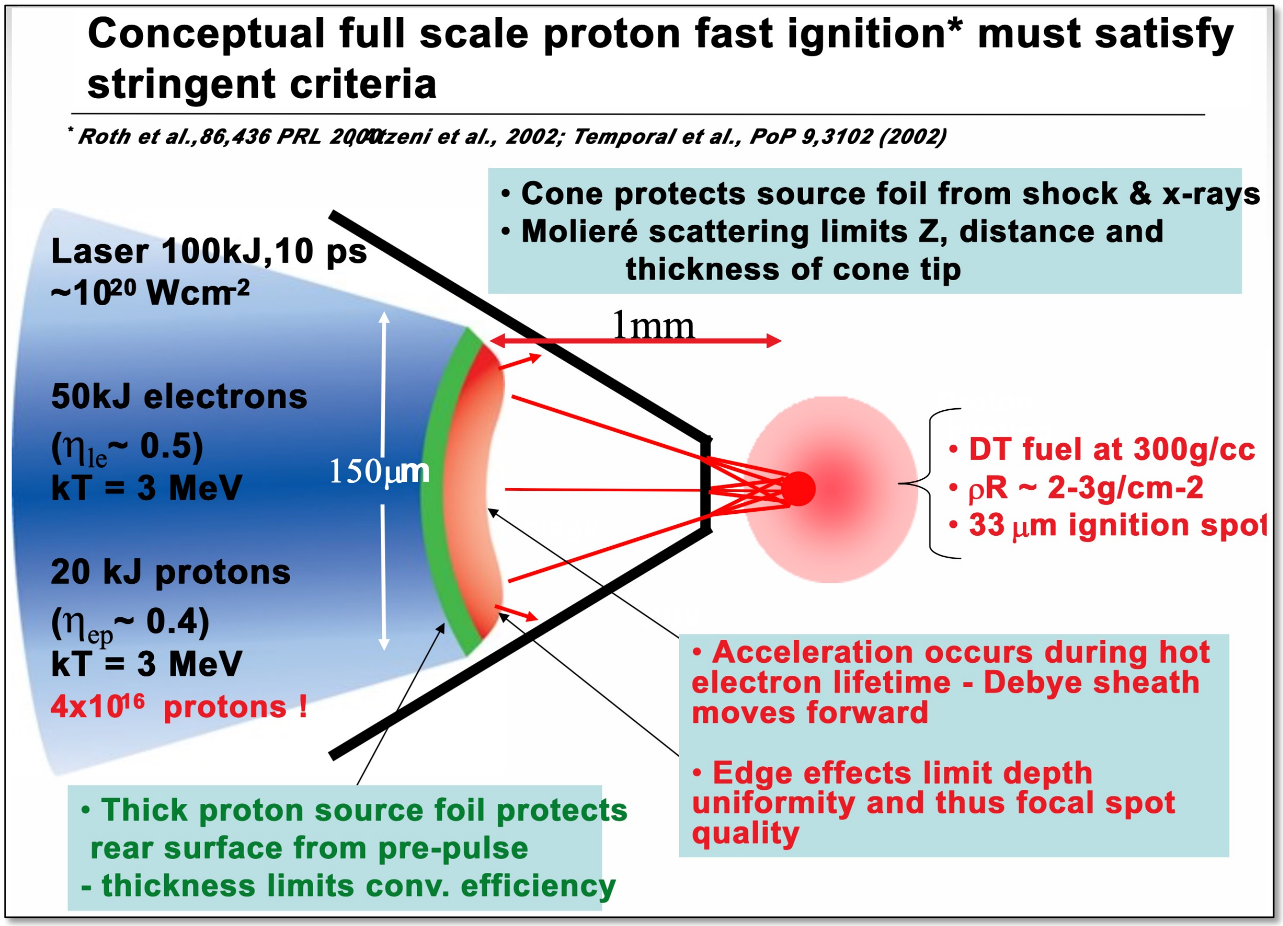
	Two-Sided Hybrid	Impact Fast Ignition*
Fuel assembly	Isobaric at $\rho R\sim 2g/cm^2$, $\rho_{HS}\sim 80g/cm^3$	Isochoric at $\rho_{HS}\sim\rho_{fuel}\sim 400g/cm^3$
Assembly pulse shape	3-shock plus main, adiabat shaped; indirect drive	Guderly-like self-similar $P(t)\sim 1/t^2$; direct drive
Ignition type	Shock ignition with thick, low-IFAR (~12) shell @$\leq 3x10^7$cm/s; direct drive Isobaric hotspot $T_i\sim 10keV$, $\rho R_{HS}\sim 0.35g/cm^3$	Impact fast ignition with thin, high-IFAR flyer-plate @~$2x10^8$cm/s; direct drive Isochoric hotspot $T_i\sim 10keV$, $\rho R_{HS}\sim 0.6g/cm^3$
Ignition pulse shape	3-shock +main +shock over t~15ns, $t_{main+shock}\sim 5ns$; $P_{max}\sim 220TW$, $I_{max}\sim 3x10^{15}W/cm^2$	Flattop over ~1ns, $P_{max}\geq 600TW$, $I_{max}\geq 6x10^{15}W/cm^2$
Issues	- Complex target fab - Indirect drive symmetry for assy - Au/C/DT drag mix during assembly - Late time shock coupling physics	- Complex target fab - Direct drive symmetry for assy - Au/DT drag mix during assembly - High density isochoric fuel assy at cone tip - Flyer plate stability

Two-sided hybrid target: Initial 2-D LASNEX simulations



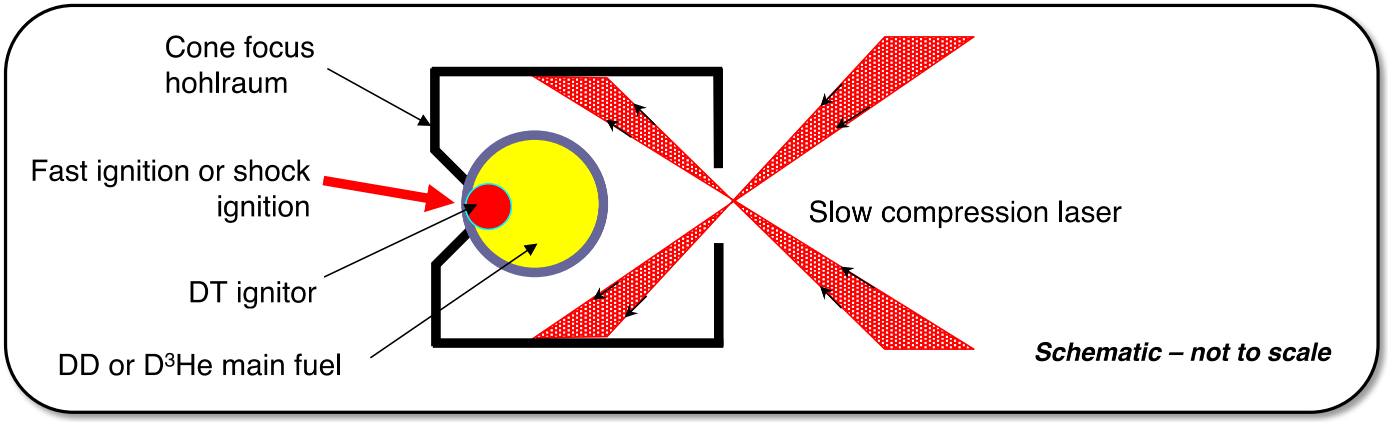
Given energy headroom of ignition side (0.53→0.9+MJ), we have the option of significantly overdriving direct drive side for more robust ignition

Proton fast ignition As with regular (laser-electron) fast ignition, it's all about the efficiency of focusing the short pulse energy into the hotspot



A. Mackinnon, LLNL (2006)

Advanced fuel targets: It might be possible to efficiently burn DD or D^3He fuels in ICF targets with DT Initiators

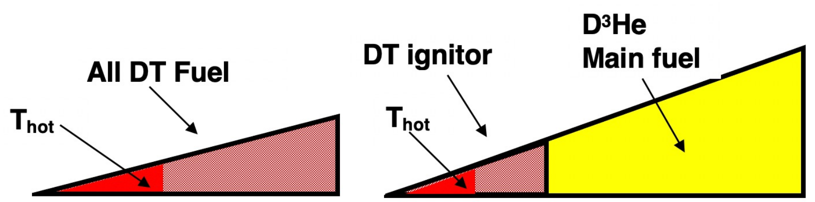


Advanced, non-DT target fuels: **DD or D^3He main fuel with self-breeding, fast-ignited DT ignitor regions.**

Features: **– DD/D^3He fuel + DT ingitor; – Overall ≤1% T_2 inventory;**
– Self breeding T_2 ; – Self-trapping of neutrons/Bremsstrahlung;
– ≤5% of yield in fast neutrons; – >90% charged particle output

Applications: **Advanced energy conversion (magnetic flux compression, MHD,….); Advanced space propulsion (directed thrust of charged particle output) ?**

Advanced fuel targets: Sample burn parametrics and escape spectra for D-T vs. D-3He



	Typical DT Compressed Fuel	Advanced Target Compressed Fuel
Fuel mass (mg)	*7*	*14*
Density (g/cm^3)	*130*	*980*
r-R (g/cm^2)	*3.0*	*15*
r-R_{DT} (g/cm^2)	*Same*	*4.0*
r-$R_{DT,hot}$ (g/cm^2)	*0.5*	*1.5*
T_{hot} (keV)	*10*	*10*
Tritium inventory	*50%*	*1%*
Yield (MJ) and partition fraction:	*317*	*850*
Fast neutrons	*0.75*	*0.08*
Radiation (no rad convertor)	*0.01*	*0.37*
Charged Particles	*0.24*	*0.55*
Fraction of yield from D-T	*> 0.99*	*0.16*
Av. peak fuel temp $\langle T_i(t)\rangle_r$ (keV)	*46*	*190*
$E_{hotspot}$ (kJ) (→ fast ignitor energy)	*37*	*16*
E_{fuel} (kJ) (→ driver energy)	*71*	*570*

L. J. Perkins
1-D Lasnex results , (2001)

From a regulatory view, NIF might be able to accommodate yields of >100MJ (my 2014 perspective!)

LLNL Site-Wide EIS 2005

- Shot budget = 1200MJ/yr
- 1.3MJ Indr-drive ign target, nom.yield = 20MJ
- Indr-drive ign target, max cred. yield = 45MJ
- 0.5rem/yr LLNL limit*

Equivalent NIF Dose Limits

- Total of ~19 person-rems/yr over all personnel**
- 30mrem/yr individual av. (⇒ ~600 people)
- 0.5rem/yr LLNL limit* (⇒ target bay workers)

(*NRC worker limit = 5rem/yr; DOE limit = 1rem/yr)

⇒ Changes to EIS to increase yield limits may be "just" paperwork until we cross the threshold to a 'Category-3 Nuclear Facility' :

Limit for *"less than Cat-3"* is 1.0

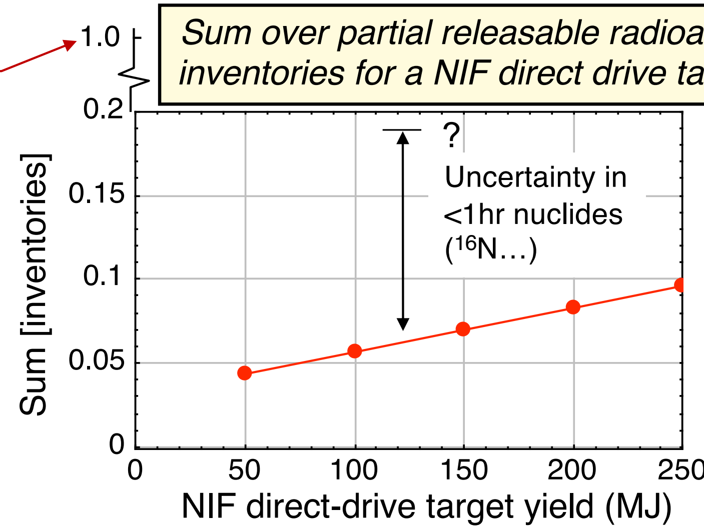
"Less than Category-3" Facility requires:

Sum **[**partial *releasable* inventories**]** < 1.0

(⇒ <10rem@30m)

Category	Example
1	Nuclear reactor,Hanford tanks
2	LLNL Pu bldg,
3	LLNL tritium bldg (≤30g T_2)
<3	Radiological facility (e.g NIF)

*Sum over partial releasable radioactive inventories for a NIF direct drive target**



* Inventories will be higher for indirect drive due to activation of hohlraum and support structure → lower max yields (TBD)

Advanced target requirements would ideally be defined through an R&D plan for Inertial Fusion Energy: Roll back from where we want to go

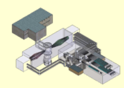
The IFE R&D program rolls back from these

World IFE Program ~2021-2030+

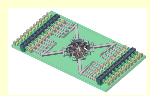
- Advanced targets on NIF*, Omega, LMJ*, Z, …
- Rep-ratable drivers (“beamlets”)
- Chambers (liquid,solid) and nuclear technology
- Support technology (target fab, injection, optics…)

*At yield and gain

High Average Fusion Power Facility ≥2030

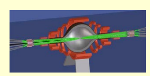


LIFE-1



FTF (KrF, Pulsed Power)

HiPER

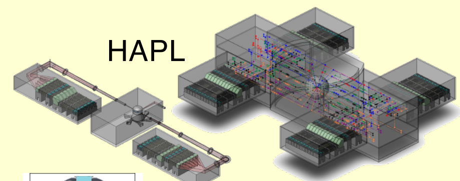


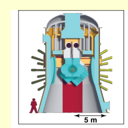
HIFTF, etc…

- High av. power 10’s-100MW from high gain targets
- Demonstrates high-average-power fusion energy
- **Not** req’d to demonstrate commercial viability

Attractive Commercial Plant Competitive with Advanced (Breeder) Fission

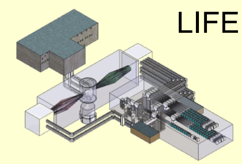
HAPL





HILIFE

LIFE

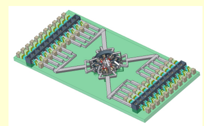


- Electricity (≥1GWe)
- Fission hybrid (breed/transm.)
- Hydrogen production
- Desalinated water
- Etc, ….

The key next-step IFE facility would be a high-average-fusion-power machine. What are its performance metrics?

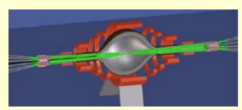
An IFE program rolls back from this

- Advanced high-gain targets
- Rep-ratable laser drivers ("beamlets")
- Chambers (liquid,solid) and nuclear technology
- Support technology (target fab, injection, optics…)

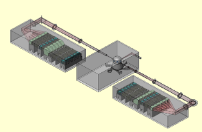


FTF (NRL)

HiPER



HI-FTF



TNA ("The Next Acroynm")

- High av power ~10-100MW (fusion or ~thermal; not electric)
- Higher gain targets: 10's @ $\lesssim$ 2 MJ
- Efficient rep-ratable driver ~1-2MJ @~5Hz
- Injectable, rep-rated targets
- Simple illumination geometry
- Long lasting chambers and optics
- One down-selected driver, with (ideally) multiple chamber concepts
- Not req'd to demonstrate the economic viability of fusion
- Is req'd to demonstrate sustainable fusion in steady state

IFE Development Path: Prospective Facility Parameters From NIF to Commercial Prototype

	NIF	TNA - High Av. Fusion Power Test Facility	IFE ETR/Demo	IFE Prototype Commercial
Total Project Cost	\$3.6B	≤\$3B	~\$3B	Economic[i]
Construction start	1995	≥2030	≥2040	≥2050
Full power operation	2010	≥2035	≥2045	≥2055
Target Chambers	Single	Multiple/various designs	Multiple/various designs	Modular/single design[a]
Net electric output	No	No (modules only[j])	100'sMWe	≥500MW_e mod. units[a]
Driver energy (MJ)	2 (3ω)	≤1	≤1	≤1
Driver direct cost (\$/J)	~1000 (3ω)	≤500	≤250	≤250
Driver efficiency (%)	<1	≥5	>10	>10
Target gains	1-200	10's-100's	100's	100's
Target yields (MJ)	≤200	100's	100's	100's
Rep-rate (Hz)	N.A	≥5	≥5	>10-20 (modular[a])
Av. fusion power (MW)	N.A	25-100	100's	1000's
Evacuation plan req'd under accident scenarios?	N.A	No. Naturally safe[e]	No. Naturally safe[e]	No. Naturally safe[e]
Early dose from design basis accident @1km	<Cat-3 DOE facility	≤0.5rem [g]	≤0.5rem [g]	≤0.5rem [g]
Worst-case chronic (7-day) early dose @ 1km	<Cat-3 DOE facility	≤5rem total [f]	≤5rem total [f]	≤5rem total [f]
Occup. dose to plant personnel	30mrem(av); 0.5rem(max)	≤1rem/yr	≤1rem/yr	≤1rem/yr
Rad waste disposal criterion	N.A	TBD[c]	Class C or better [d]	Class C or better [d]
Demonstrate closed fuel cycle?	N.A	No	Yes	Yes
Availability of fusion power core [h]	N.A	Low	>50%	>95% [b]
Mass manufactured targets	No	Yes, @ 5Hz[k]	Yes, @ 5Hz, ≤30¢/target	Yes, @ 5Hz, ≤30¢/target

These (speculative) dates are constrained, at least, by the prior R&D program for high gain targets

That old adage: What's the difference between ICF and IFE?

- In *Inertial Confinement Fusion (ICF)*, you have to show you can do it once
- In *Inertial Fusion Energy (IFE)*, you have to show you can do it 10-times a second for 30-years at 95% availability, 10-cents a target and a COE of 5 ¢/kWh !

  ⇒ One essential step:- High gain targets (Strive for gains ≳100 at 1MJ)

Lawrence Livermore
National Laboratory